UNITED STATES
DEPARTMENT OF THE INTERIOR
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GEOLOGIC EVALUATION OF 3-5 MICROMETER INFRARED IMAGERY AND COLOR PHOTOGRAPHY IN SOUTHERN UTAH

by

Robert J. Hackman

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This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

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ABSTRACT

A comparison of 3-5 micrometer, afternoon and midnight infrared (IR) imagery and color photography with conventional aerial photography shows that IR imagery and color photography have some unique capabilities. In general, the IR imagery provides in shades of gray a record of the relative ground temperature at the time the image was taken. It has day or night capabilities for imaging large areas of terrain. In sparsely vegetated areas, midnight IR imagery shows some tonal variations that may be related to specific rock type based on temperature differences. In heavily vegetated areas, any temperature difference that might exist between rock units is masked by the temperature difference associated with different vegetation communities; although, isolated outcrops in such areas are generally apparent because they are brighter (warmer) on the afternoon IR. On the midnight IR they may or may not be brighter according to their differences in thermal inertia. The afternoon IR image showed one fault that was not visible on the aerial photographs. In contrast, only some of the faults visible in the stereoscopic model were recognized on the IR imagery. The interpreter using IR imagery must be aware of changes in heat patterns resulting from modification of the land by man and from the effect of cloud shadows. Apparent anomalies on IR image resulting from such factors might be misinterpreted. Compared to conventional photography with the added ability of stereoscopic viewing the day and night IR provided less geologic information in the area of study. IR imagery may be useful in hydrologic studies such as the relative temperatures of alpine lakes, ponds, and marshes during the night and day. It should prove

valuable in ecological studies involving the relative temperatures of different plant communities. Roads in heavily wooded areas are easier to see on the IR image, than on conventional photography because of their temperature differences.

Color photography, as might be expected, shows the terrain in a close approximation to its natural color, and delineates some stratigraphic units and rock alterations that are indistinguishable on black and white photography.

INTRODUCTION

Infrared (IR) imagery has been used to study areas of anomalously high terrestrial heat flow associated with active volcanoes (Fischer, et al, 1964, Moxham and Alcaraz, 1966, Moxham, 1967, and Friedman and Williams, 1968), and hot springs and geysers (Moxham, 1968); and has been used to record the infrared emission of rocks heated by solar radiation (Cantrell, 1964 and Sabins, 1967). The IR study described in this report falls in the latter category and was undertaken to evaluate the geologic capability of both afternoon and midnight 3 to 5 micrometer IR imagery in contrast to black and white aerial photography. Color photography was taken simultaneously with the afternoon IR to assist in identification and location and also for evaluation of its capabilities in contrast to the IR imagery and black and white photography.

The IR imagery and color photography evaluated in this report cover a strip 5 to 10 miles wide extending northward one hundred miles in southern Utah, from Henrieville in Garfield County to Salina Canyon in Sevier County. It also includes a shorter strip from Salina Canyon near the town of Salina southwestward for about fifteen miles (fig. 1). The imagery and photography were taken on August 8, 1966 by the HRB Singer Corporation, under the sponsorship of the U. S. Geological Survey and the National Aeronautics and Space Administration (NASA).

Adverse weather conditions present at the time the IR imagery was taken, have no doubt reduced the quality of the IR imagery used in this study. Geologic and related interpretations made from this imagery do not necessarily provide a full measure of the capability of top quality 3 to 5 micrometer IR imagery.

The IR imagery was taken by an airborne optical-mechanical imaging infrared radiometer (Reconofax IV) equipped with a selective filter for recording only 3 to 5 micrometer wave length radiation. The color photographs are on Kodak Special Ektachrome MS Aerographic (ESTAR) Type 50-151 film. Both color and daytime IR were taken between 4:08 P.M. and 4:49 P.M. The IR imagery is a continuous strip; the color photography is 9 x 9 inch frames with 5 percent overlap. The midnight IR imagery was taken between 12:00 P.M. and 12:34 A.M. and over the longer strip only, extending from Henrieville to Salina Canyon. Only midnight and afternoon IR imagery, referring to the above mentioned times, are evaluated in this report. It should be pointed out that there are substantial differences between features shown on nighttime IR imagery made "post-sunset," at midnight, and "pre-dawn" and daylight imagery made "post-sunrise," at noon, and "pre-sunset."

VARIABLES THAT AFFECT INFRARED IMAGERY

The operation of an imaging infrared scanning device has been described by Cantrell (1964). It records an image whose gray scale is controlled by the instantaneous energy focused upon a detector. Energy emitted or reflected from the earth's surface is selectively absorbed by the atmosphere so that only that part which passes through the atmospheric window reaches the airborne detector (Fischer, et al, 1964). Windows commonly used in the infrared region are at 3 to 5 micrometers and 8-14 micrometers.

Reflected solar radiation peaks at approximately 0.5 micrometer, but decreases rapidly and above 3.5 micrometers is usually negligible in thermal mapping studies (Blythe and Kurath, 1967). Some of the brighter tones or highlights associated with west-facing slopes and visible on some of the late afternoon IR images shown in this report are probably enhanced by reflected radiation.

Cantrell (1964) points out that absorbed radiation is generally emitted from the earth's surface in the longer infrared wavelength region between 5 and 20 micrometers. Infrared imagery of this area of study taken through the 8 to 14 micrometer window would no doubt provide considerably more interpretative information.

IR images do not have the resolution, scale stability, and geometry of the conventional aerial photograph. The lack of these characteristics is often a disappointment to the viewer unfamiliar with IR imagery. Spatial resolution is inferior to that of conventional photography and the wide angle view provided by the scanner is confusing with regard to geometry and scale.

The picture is not a photographic image formed by reflected light but an image whose tones of gray are indicative of emitted radiation in the infrared region. The relationship between tones of gray on the film and radiant temperature is not quantitative because of the inability of the film to record lineraly the complete range of temperatures encountered. Also the electronics in the system are often nonlinear.

The interpretation of IR imagery must take into consideration many characteristics of the earth's surface that greatly affect the amount of solar radiation that is absorbed and reflected. According to Baver (1948, p. 288), these variables are (a) the angle at which the sun's rays strike the surface, (b) the presence of large bodies of water, (c) the physical characteristics of soil and rock, (d) the presence of vegetation, and (e) the effect of elevation on temperature. In addition to these variables discussed by Baver, due consideration should be given to (f) temperature difference resulting from wind, and relative humidity and (g) modification of the surface by man.

Sun angle: The angle at which the sun's rays meet the earth greatly influence the amount of radiation received per unit area. Radiation reaching the earth at a 30 degree angle is scattered over a wider area than the same radiation striking the earth's surface perpendicularly. The effect of the angle of solar radiation is apparent on the illustrations used in this report, where many of the northfacing slopes and cliffs are noticeably darker (cooler) than adjacent areas.

Large water bodies: Large bodies of water (none are present in this area of study) tend to stabilize local temperatures because of the high specific heat of water, which allows the absorption of large amounts of solar energy. Smaller bodies of water such as mountain lakes, reservoirs and marshes, which are present in the area have very little affect on the local temperature. However, the relative size and depth of water of these features, with due consideration given to convection cooling and differences in mixing of surface water by wind and current, does affect the rate of heat absorption during the day and its subsequent emission at night. The rate of heat absorption during the day and its subsequent emission at night of these smaller bodies of water is related to the size, depth, convection and differences in mixing of surface water by wind and current.

Characteristics of soil and rock: The critical property in determining the rate of cooling of rock and soil is thermal inertia. Thermal inertia is equal to the square root of the product of thermal conductivity times density times specific heat.

The surface of a rock with low thermal inertia will heat more rapidly than that of a rock with high thermal inertia when both are exposed to the same radiant flux. The surface temperature of low thermal inertia rocks will cool more rapidly when the source of radiant energy is removed. For example: gypsum has a lower thermal inertia than dolomite and its surface would heat more rapidly than dolomite, also its surface would cool more rapidly. Laboratory studies by Sabins (1967) showed that siltstone, because of its lower thermal inertia, heated to 37 degrees centigrade (midday) while sandstone of the same color, but higher thermal inertia, heated to 35 degrees. By midnight there was a thermal crossover: the siltstone cooled faster than the sandstone.

When water is added to soil or rock it fills pore space, replacing air with liquid. The result is an increase in thermal conductivity, density, and specific heat, thus, increasing the thermal inertia. Wet sand would, therefore, be cooler than dry sand on IR imagery made in the morning; but by afternoon the surface temperature difference would be small because of the equalizing effects of atmosphere. After sunset the wet sand would be warmer than the dry sand, but it would cool more rapidly until both attained the same temperature sometime between midnight and dawn.

Talus slopes and surfaces covered with blocky material generally will show higher surface temperature at night because irregular surfaces trap back-radiation (black body cavity effect).

Effect of vegetation: According to Baver (1948, p. 291) the major effect of vegetation on soil temperature is insulation. Bare soil and rock are unprotected from the direct rays of the sun and become very warm during the hottest part of the day. At nightfall, unprotected soil and rock, in general, rapidly lose their absorbed heat to the atmosphere, the rate of loss depending on their thermal inertia. On the other hand, a good vegetation cover intercepts a considerable portion of the sun's radiant energy, preventing the surface beneath from becoming as warm as bare soil or rock during the day. This insulation effect is due to the fact that leaves are nearly opaque to IR wave lengths of 2.5 micrometers and longer; thus very little solar radiation reaches the ground (Blythe and Kurath, 1957). A further factor is the cooling effect of transpiration of water from plant leaves (Baver, 1948, p. 293). At night, transpiration from the leaves is considerably reduced and the vegetation acts as an insulating blanket that reduces the rate of heat loss from the soil. Consequently, a protected soil is cooler during most of the day and generally warmer at night than bare soil or rock (fig. 2). There is also a temperature difference related to different types of vegetation. For example, the temperature of the ground under a forest cover is cooler during the day than under a grass cover, and conversely, is warmer at night. The high emissivity of living vegetation is also a factor.

Elevation difference: The decrease in temperature in middle latitudes up to an elevation of 13,000 feet is just under one degree Fahrenheit per 300 feet of elevation (Rudaux and De Vaucouleurs, 1959, p. 91), if the effect of local meterological irregularities are not considered. This change in temperature does not generally affect the absorption capability of surface features but does affect the rate at which they cool, especially at night. Since the rate of cooling is approximately proportional to the temperature difference between the rock and air. The same rock type will cool more rapidly at a high than low elevation.

Wind and relative humidity: High surface winds, humid air, rain, and cloud shadows greatly reduce the normal IR image quality and mask or subdue ground surface temperature differences that might otherwise be present.

Surface modification by man: Modification of the surface by man, such as roads, clearing, logging operations, pipelines etc. locally affect the normal heat picture of the surface of the ground.

General capabilities of color photography

The use of color as a valuable tool in geologic mapping has been discussed in the literature (Laylander, 1956; Kent, 1957; Fischer, 1958, 1962; Minard, 1960). According to Evans (1948, p. 120), the human eye can recognize 125 hues in the spectrum, and for some of these, 200 steps of saturation. This, plus variation in brightness or lightness provide the viewer with hundreds of thousands of recognizable colors, a large percentage of which are recorded on photographic film. In contrast, colors appear on black and white film as shades of gray, in which only about 200 shades can be discerned. Thus, color photography is of great value to the photointerpreter.

Method of study

The IR imagery was enlarged two times for better viewing and for easier comparison with 1:60,000 black and white aerial photography of the area. The IR imagery and the black and white photography were also compared with the color photography, scale 1:18,000 to 1:48,000. A stereoscopic evaluation of the latter could not be made because the overlap of individual frames is only 5 percent. Much of the color photography was of low contrast and very dark because of considerable cloud shadows on the ground at the time of exposure.

The flight line of the night IR did not closely follow that of the day IR and only in a few places was it possible to compare the two images. Unfortunately, the best area of overlap was where the color photography showed complete cloud shadow coverage on the ground.

The geology of most of the area had been annotated on the 1:60,000 black and white photographs. These annotations were made in part from available geologic maps and in part from field work by the authors in the summers of 1965, 1966, and 1967 in connection with the compilation of the Salina and Escalante 2 degree geologic quadrangle maps. The imagery and photography were compared with the geology to ascertain their relative merits in providing geologic information.

Geology and ecology

Physiographically the area of study is in the southern and eastern part of the High Plateaus of Utah Section of the Colorado Plateau Province (Fenneman, 1931), and from north to south includes parts of the Sevier Valley, the southern end of the Wasatch Plateau, Fish Lake Plateau, Thousand Lake Mountain, Rabbit Valley, Awapa Plateau, Aquarius Plateau and Table Cliff Plateau. Structurally and stratigraphically, the High Plateaus are a transitional zone between the Basin and Range province on the west, and the Colorado Plateau Province on the east. Two major tectonic features in the area are the southern part of the Wasatch monocline, near Salina, Utah, and a part of the northern end of the Table Cliff Syncline. Many north-trending faults of considerable magnitude are in the area. Sedimentary rocks range in age from Jurassic to Tertiary with a considerable part of the area capped by volcanic rocks of Tertiary and Quaternary age. Quaternary surficial deposits occur throughout the area.

The climate varies from desert near Henrieville, elevation 5,000 feet, where annual precipitation is 5 to 6 inches, to alpine, elevation 10,000 to 11,000 feet, where precipitation is 25 to 30 inches. There is a wide variety of both residual and transported soils. The flora varies in type from southern desert to alpine scrub, the lowlands lying on the outskirts of lower Sonoran territory and the summits on the tension line between sub-alpine forest and the arctic-alpine desert. The timber line is determined by wind rather than by temperature, so broader summits favor better development of forest. Small tables and isolated peaks are occupied mostly by alpine scrub; larger tables such as Aquarius and Fish Lake Plateaus and Thousand Lake Mountain, by parklike arrangements of scrub and forest cover (Dixon, 1935).

Interpretation and evaluation

Since it is not feasible to show and discuss all the IR imagery and color photography used in this study, some representative samples have been selected to illustrate capabilities of the two in different types of terrane. More emphasis has been given to the evaluation of the 3-5 micrometer IR imagery than to the color photography simply because contrasts in color are obvious; most people can easily ascertain the capabilities of color photography.

Figure 3 shows an annotated aerial photograph, a midnight IR image and and afternoon IR image of a portion of the Aquarius Plateau in Southern Utah. The area is at an elevation of 9,000 to 10,000 feet and is 60 percent forest (mostly conifers) interspersed with grassy and sage covered meadows. A very thin residual soil covers much of the area. Some alluvium and colluvium are present. Outcrops are numerous, both in the open meadows and in the woods. Two major rock units are present: basaltic andesite of Tertiary age overlain in part by olivine basalt of Tertiary and Quaternary age. The color photograph (not shown) taken at the same time as the afternoon IR image shows the area is mostly covered by cloud shadow. The difference in surface and/or air temperature resulting from the cloud shadow is more apparent on the left half of the IR image. It is less noticeable on the right half of the image, since during overflight, the IR signal gain was advanced approximately mid way across the area to compensate for the overcast ground condition. The change in temperature resulting from cloud shadow is especially noticeable in the open meadows such as at C and D.

In comparing the afternoon and midnight IR images, note the inversion of tone values. During the day the meadows are warmer (brighter) than the cooler (darker) wooded areas. In contrast, at midnight the meadows are cooler (darker) than the warmer (brighter) wooded areas. Some brighter areas, as at (A) and (B), appear in the woods on the night IR. Such areas are generally on steep south-facing slopes where tree density is less and outcrops more abundant. Because of higher sun angle, these rocks receive a greater amount of radiation during the day and are still warmer than the surrounding woods at this time of night.

The brighter (warmer) areas near the bottom of the midnight IR image include the cliff-forming edge of the basaltic andesite and landslide detritus forming the south-facing slopes below this cliff. The tree density is less on these slopes and the landslide detritus consists of large blocks of basaltic andesite. The irregularities of this surface no doubt trap back-radiation (black body cavity effect). Also such rock materials have a higher thermal inertial than nearby soil. It is possible that warm air rising from the desert area to the southeast may contribute to the higher temperature.

The surface of two water bodies, Cyclone Lake and Roundy Reservoir, have the brightest (warmest) tone value on the midnight IR. They are still emitting absorbed heat and are warmer than any other feature on top of the plateau. Two very shallow ponds are just north of Cyclone Lake at F and G. On the midnight IR both have already lost what little absorbed heat they had and are cooler (darker) than the adjacent wooded areas.

The contact between the basaltic andesite and the olivine basalt was mapped in the field by the authors and is annotated on the aerial photograph. This contact could not be recognized in the stereoscopic model of the aerial photograph; there appears to be no geomorphic or geobotanical contrast between the two rock units. The contact indiscriminately crosses meadows and forested areas. On the IR images, there is likewise no evidence of a difference in rock type. The temperature difference between the wooded areas and the meadows masks any heat pattern difference that might exist between the two rock units. However, if this area were unvegetated it is doubtful that the IR imagery would show any contrast between these two units, because there is very little difference between their thermal inertias. Post-sunset IR imagery might pick up a difference. Also, 8-14 micrometer imagery would provide a better means of detecting such subtle temperature difference.

Faults in this area are quite evident in the stereoscopic model of the aerial photographs but are not defined on the IR imagery.

It is apparent that very little information of geologic significance can be obtained from the IR imagery in this area. The images do provide some hydrologic data on heat absorption and emissivity and relative temperature difference of lakes and shallow ponds. The IR images indicate differences in ground temperatures associated with different vegetation communities during the day or night, a fact useful to the geologist.

Figure 4 shows some effects of man-made features on IR images near the southern edge of the Aquarius Plateau. This area is in general similar to that of figure 3. Some striking lineations on the IR imagery might be interpreted as fault or fracture lineations. Field investigation, however, reveals these to be parallel logging swaths that have been cut through the woodlands since 1954, when the black and white photography was taken. The swaths are warmer than the adjacent woods during the day and are cooler at night.

In addition to the prominent man-made lineations some less conspicuous ones appear on the midnight IR image (AA, BB, CC, DD, and E). These lineations represent the traces of faults that were mapped in the field by the authors. The fault traces are generally darker (cooler) than the adjacent areas. Factors associated with each fault which may affect the absorption of solar heat during the day and its subsequent loss during the night with respect to adjacent areas are: (1) a greater amount of moisture along the faults; (2) a greater abundance of outcrops on the scarps of the upthrown side of the faults; and (3) a greater angle on the fault scarps. These faults and their displacements are visible on the aerial photographs, especially under stereoscopic viewing.

The southern end of the Table Cliffs Plateau is shown in figure 5. The elevation range in the area covered by the photograph and the two IR images is from 8,000 feet to 10,200 feet. With the exception of the small area underlain by welded tuff of Tertiary age, the greater part of the forested (mostly coniferous) plateau surface is underlain by a massive microcrystalline limestone unit of the Wasatch Formation of Tertiary age (Gregory and Moore, 1931, p. 114 and Bowers, 1968). On the midnight IR image, there appears to be a noticeable tone break between the massive limestone beds and the underlying older units. The limestone is darker (cooler) than the underlying brighter (warmer) units. Thus, the limestone by midnight appears to have lost any heat that it might have absorbed during the day in contrast to the lower units, or it absorbed less heat than the other units.

The intrinsic difference in heat absorption and/or heat retention between the massive limestone and the other rock units is most apparent at A on the midnight IR. The photograph and the geologic map show that there is essentially no vegetation cover at this point and that the limestone is overlain by the uppermost unit of the Wasatch Formation consisting mostly of mudstone and sandstone, and underlain by a calcareous mudstone and sandstone unit of the Wasatch Formation. Both the units above and below the limestone are brighter (warmer) than the darker (cooler) limestone. Some of the brighter (warmer) bandings are the result of a temperature difference associated with vegetation growing along some of the bedding planes.

The brighter (warmer) band at the base of the Tuff of Osiris (see B on the midnight IR) may represent a warmer cliff face of latite. Possibly the bright band is caused by the black vitrophyre that occurs at the base of the tuff. It is possible that this band could be caused by talus at the base of the cliff.

Although the wooded areas such as C on top of the limestone surface are brighter (warmer) than adjacent clearings such as D on the midnight IR image, they are, as might be expected because of the elevation difference, not as bright (warm) as wooded areas at lower levels such as at E. The access road is clearly visible on both the midnight IR and afternoon IR (F) in marked contrast to the photograph where it is only partially visible in the stereoscopic model under increased magnification. Unpaved roads in wooded areas generally show up like cleared areas, i.e., cool at night and warm during the day. Comparison of the coniferous tree-covered areas around G and H on the photograph with the same areas on the afternoon and especially the midnight IR indicates a noticeable difference between thermal patterns of these two areas. An examination of the color photography (not shown) taken at the same time as the afternoon IR shows that recent logging operations near G have resulted in numerous clearings which appear on the midnight IR as darker (cooler) spots and on the afternoon IR as brighter (warmer) spots, resulting in a mottled pattern.

In areas of lower elevation and reduced tree density the heat holding capacities of certain rock units seem more apparent. Figure 6 shows an area in Salina Canyon. On the midnight IR image the massive sandstones and conglomerates of the Price River Formation of Cretaceous age appear brighter (warmer) than the underlying shale, thin sandstones and coal beds of the Black Hawk Formation of Cretaceous age and the overlying variegated shales and thin sandstones of the North Horn Formation of Cretaceous and Tertiary age. The sandstones and conglomerates apparently retain solar heat for a longer period of time than do the adjacent beds. The heat pattern delineating the sandstones and conglomerates in many places is modified by the effect of talus and slope wash and is not always sharp. Also, north-facing outcrops such as A, B and C receive less solar radiation during the day and consequently appear darker (cooler) on the night IR image.

It is possible that the cooler (darker) areas on the midnight IR imagery are caused by ponding of cool air at night in the valleys. Because of the generally flat lying beds, this would make the cooler areas roughly follow lithologic boundaries. There also seems to be a relationship between density and/or type of vegetation and lithology in the aerial photograph. Similar differences of radiant temperature can be seen on the midnight IR image. It is not apparent whether it is vegetation or the lithology that is responsible for the temperature difference shown on the IR image--probably a combination of both.

A noticeable difference in ground temperature is apparent on the midnight IR image where displacement along the fault (located near the bottom of image) has dropped the North Horn Formation to the level of older rock units. Here, the North Horn Formation is partly covered by slope wash and like the darker (cooler) alluvium mapped to the northwest supports a vegetation mostly of sagebrush and/or grass. It is probably this vegetation difference that is expressed as a darker (cooler) area on the midnight IR image and generally delineates the fault. The faults in the upper part of the IR image are less apparent because of the oblique view of the area.

On the midnight IR image the brighter (warmer) line in Salina Canyon is a macadam-surfaced highway. If cool air were ponding in the valley one would expect the road alignment to be diffused.

Figure 7 shows another area underlain by flat-lying sedimentary rocks. Elevation difference in the area is from 7,100 to 8,400 feet. From base to top, stratigraphic units are: the upper part of the Moenkopi Formation; the Shinarump, Middle and Upper members of the Chinle Formation; the Wingate Sandstone; and the Kayenta Formation, all of Triassic age; the Navajo Sandstone of Triassic and Jurassic age; and the Carmel Formation of Jurassic age. Based on temperature difference alone, as seen on the midnight IR, the following contacts can be approximately delineated: The Navajo-Kayenta contact; the Kayenta-Wingate contact; the contacts between the Upper and Middle and between the Middle and Shinarump Members of the Chinle Formation; and, rather poorly defined, the Chinle-Moenkopi contact. The Navajo and Wingate Sandstones, the upper part of the Middle Member of the Chinle Formation and the Shinarump Member of the Chinle Formation generally appear brighter (warmer) than the adjacent, darker (cooler) silty and shaly units such as most of the Middle Member of the Chinle Formation and the Moenkopi Formation. The darker (cooler) tone of the Kayenta Formation is probably due to the vegetation cover and also the presence of siltstone and mudstone in this predominantly sandstone unit.

On the midnight IR image the massive Navajo Sandstone, except at its base, is not as bright (warm) as sandstones lower in the section because of the insulating effect of a dense coniferous forest cover. This cover also obscures the Navajo-Carmel contact.

In the general area of A, B, and C, the bedrock is poorly exposed and mostly covered with volcanic boulders and slope wash. These areas appear brighter (warmer) on the night IR. Most of these deposits are on west to southwest facing slopes and solar radiation is more recent and more direct on these slopes; also, boulder slopes are warmer because of black-body cavity effect and higher thermal inertia of the volcanic boulders.

Figure 8 shows a sparsely vegetated area near Salina, Utah, at an elevation of 5,500 feet. Folded sedimentary rocks of Jurassic and Tertiary age are capped by generally flat-lying volcanic rocks of Tertiary age. The afternooon IR image shows a lineament, AB, which appears to be a continuation of a fault between the Twist Gulch Member of the Arapien Shale and the Flagstaff Formation and probably reflects differences in surface texture and possibly moisture content. This lineation is not apparent on the color and black and white photograph. The generally darker (cooler) areas in the alluvium are probably due to ponding of cool air at night rather than cultivation and irrigation.

Differences between rock units are not very apparent on the afternoon IR image, not even the obvious one between the Arapien Shale and the volcanic rocks. This lack of contrast suggests that these units may have the same surface temperature. However, since some reflected solar radiation is recorded in the 3-5 micron range and since the brighter colored Arapien Shale is an excellent reflector in contrast to the darker volcanic rocks, it is possible that the added reflected energy masks any tonal contrast representing heat differences that might exist.

Besides the above mentioned contact some others between stratigraphic units shown on the geologic map can be recognized on the aerial photographs. Unit E of the Twelvemile Canyon Member of the Arapien Shale, the Twist Gulch Member of the Arapien Shale, and the Flagstaff Formation are the same red color on the color photograph and the same shade of gray on the black and white photograph. Units A, C, and D of the Twelvemile Canyon Member of the Arapien Shale have the same brownish gray tone on the color photograph and a brighter shade of gray on the black and white photograph. However, on the color photograph the lower part of Unit C is a reddish brown color. This difference is not clearly discernible on the black and white photograph.

In this area, most of the geology that is recognizable on the color photograph is also recognizable on the black and white photograph. The ease of recognition, however, is greater on the color photography. For example, the extent of the older gravels, Qg, not all of which are shown on the geologic map, can be readily identified on the color photograph. The distribution of alluvium and alluvial fan deposits is much more apparent on the color photograph. Also, rock units can be delineated by color. On the black and white photograph similar shades of gray do not always represent the same color. In the field, it is easier to correlate the color of stratigraphic units to their related colors on the photograph than to their gray scale counterpart on black and white film.

Based on color alone, the identification of isolated outcrops in a generally forested area such as the Fish Lake Plateau was facilitated by the use of the color photography. Such identification, however, requires considerable field knowledge of the area and, although correlations were generally correct, they were sometimes in error because of intraformational color variation.

Epigenetic rock alteration is commonly expressed by conspicuous color changes. Kent (1957) describes a study conducted near Goldfield, Nevada, where rock alteration mapped from color differences on aerial photographs was confirmed by analysis of thin sections. In the present study, epigenetic alteration in the Navajo Sandstone, which caused bleaching of the rock from red to white, is clearly shown on color aerial photographs. Conclusions regarding color and alteration closely parallel those resulting from a detailed study by the junior author of color variation and alteration in the Entrada Sandstone in the Moab 2 degree quadrangle. The Entrada Sandstone, like the Navajo Sandstone, is an eolian quartzose of Mesozoic age.

Figure 9 shows a geologic map, a black and white aerial photograph, and a color aerial photograph of a small area northeast of Bicknell, Utah, part of a large area mapped by Smith and others (1963). The small area is underlain by well-exposed, flat-lying rocks of Mesozoic age, about 2,500 feet thick, cut by several normal faults, most of which are of small displacement; the Thousand Lake fault, however, has a throw of several thousand feet. The Navajo Sandstone underlies much of the area and is about 1,000 feet thick. The lower half of the formation is red to reddish-brown; the upper half is bleached white and yellow. The color boundary between the red and bleached sandstone is scarcely discernible on the black and white aerial photograph, but is conspicuous on the color aerial photograph.

Table 1 shows the color of the red and bleached sandstone as determined from typical specimens of sandstone and from the color aerial photograph. Color designations are those of the Munsell Soil Color Charts (Munsell Color Company, 1954)[1/] from which the colors were determined. Rock colors on the aerial photograph are remarkable similar to the colors of the hand specimens. For both red and bleached sandstones, the hue (position of the color in the spectrum) are nearly the same on the photograph and hand specimens. But the colors on the photograph are lower in chroma (amount of color) and value (total light reflectance) than equivalent colors in the hand specimens. Several factors might account for this: the effects of weathering would appear on the photograph but not on the specimens, which were taken of fresh rock; on the photograph, the vegetation would darken the image; if the ground were damp, the colors on the photograph would appear darker than those of the dry specimens; and certain conditions of lighting at the time the photograph was taken, or of exposure during printing, might produce a darker image.

[1/] Munsell's three variables of color, hue, chroma, and value, correspond roughly to those cited earlier in this paper, hue, saturation and brightness or lightness (Evans, p. 215) and used by the American Optical Society.

Table 1.-- Colors in the Navajo Sandstone determined from hand specimens and from an aerial photograph.

	Rock sample		Aerial photograph	
Red sandstone	2.5 YR 6/6	light red	5 YR 4/4	reddish brown
Bleached sandstone	10 YR 8/1	white	2.5 Y 6/2	light brownish gray
	2.5 Y 7/4	pale yellow		

Bleaching in the upper part of the Navajo Sandstone is clearly stratigraphically controlled; the upper half of the formation, which contains less silt and clay and less carbonate cement, is more permeable and therefore would be more susceptible to alteration by solutions passing through the rock. The bleaching is also clearly epigenetic; the upper few feet of beds in the red, less permeable sandstone, are bleached white adjacent to the upper permeable sandstone. The red-white contact in these beds does not follow bedding planes in detail, but cuts irregularly across them on a small scale. Time was not available to make a detailed study of the alteration, but it is reasonable to postulate that the upper more permeable part of the Navajo Sandstone was bleached by solutions rising along the Thousand Lake Fault.

Conclusions

IR imagery taken near midnight shows some tonal variations that may be related to specific rock type. This is especially true at lower elevations where vegetation and soil cover are sparse. Light colored sandstone and conglomerate, where massive and cliff forming, show up brighter (warmer) on the IR image than adjacent rocks such as shales, siltstones and limestones which appear darker (cooler). At higher elevations the temperatures associated with forest and meadow vegetation types mask any major temperature difference that might exist between rock types. Scattered outcrops in mostly vegetated areas can often be located on afternoon IR imagery by their brighter (warmer) appearance than the adjacent vegetation. On the midnight IR image they may or may not be brighter depending on their diurnal absorption and subsequent nocturnal emissive characteristics. In contrast, some rock units which were readily distinguishable on the ground and on conventional photography could not be differentiated on the IR imagery.

Afternoon IR imagery revealed one fault trace in the area of study that was not recognized on the black and white and color photography. In contrast, some of the faults visible in the stereoscopic model of the photography were not visible on the IR imagery. Likewise, the displacement of rocks associated with normal faulting was difficult to ascertain.

Some anomalies found on the afternoon IR images are the result of scattered cloud shadows. Such anomalies could be misinterpreted if the cause were not known. Simultaneous black and white or color photography on which clouds and cloud shadows can be recognized resolve the problem.

Compared to conventional black and white aerial photography, which has the added capacity of stereoscopic viewing, the afternoon and midnight IR imagery of this area in general provides far less geologic information. The IR imagery provides less information than the color photography, even though the latter, because of limited overlap, could not be viewed stereoscopically. In one area, however, the color photography was less useful than afternoon IR imagery: cloud shadows made the color photography completely dark, whereas the IR day image taken at the same time gave a rendition of surface features although the contrast of tone values (heat differences) was reduced because of the shadows.

Better quality 3 to 5 micrometer IR imagery would no doubt provide more geologic information; also, longer wavelength IR imagery through the 8 to 14 micrometer window, where a greater amount of emitted radiation is recorded and reflected radiation is nil, would most likely yield more interpretive data.

IR imagery may be useful in hydrologic studies of alpine lakes and ponds. Most lakes are cooler than the surrounding terrain and appear darker (cooler) on the afternoon IR; in contrast, the lakes are slower in releasing their daytime absorbed heat and are warmer at night than the surrounding terrane, and appear strikingly brighter (warmer) on the midnight IR image. In contrast some very shallow ponds appear warmer on the afternoon IR image and cooler on the midnight IR image.

Similarly, IR should prove valuable in ecological studies involving the relative temperatures associated with different vegetation communities, both during the day and night.

On IR imagery, roads through wooded areas show up better than on conventional aerial photographs.

Color photography shows the terrane in a close approximation of its natural colors, and is therefore a great aid in photogeologic interpretation. In the area of study, as would be expected, some rock units were delineated in color that were indistinguishable on black and white photography. This is not surprising in view of the many variations of color that can be recognized compared with the limited shades of gray which represent them on the black and white photography.

Color photography helps identify isolated outcrops in wooded and soil-covered areas where the recognition of the color is a critical factor in identifying the formation.

In alteration studies within a formation, color photography is an excellent tool. In one case in the area of study, red and bleached sandstones appear in very nearly their true colors on color aerial photographs.

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Figure 1. Map showing area covered by infrared imagery and color photography described in this report. Midnight infrared indicated by hachured pattern; afternoon infrared and color photography, dotted pattern.

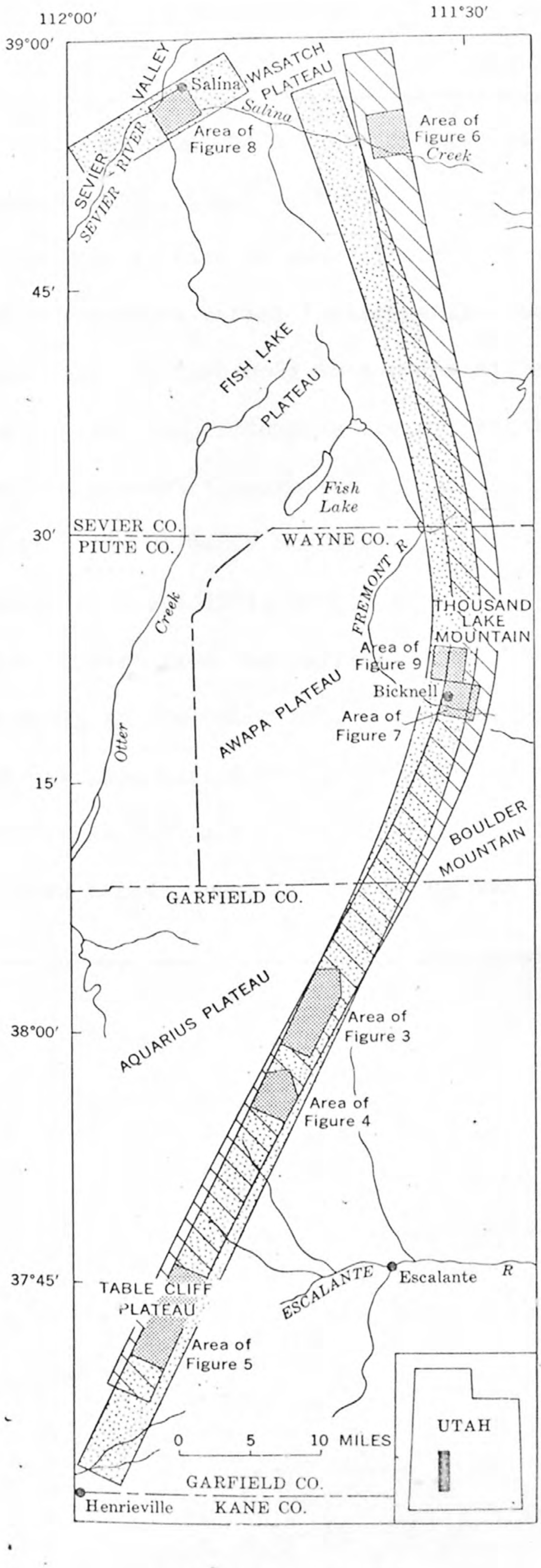
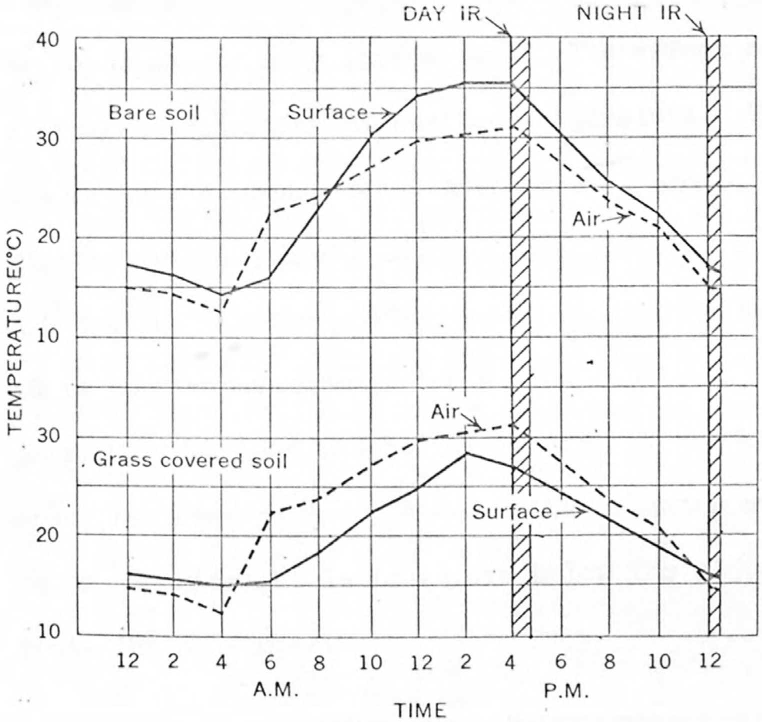

112°00′
111°30′
39°00′
45′
30′
15′
38°00′
37°45′
SEVIER VALLEY
SEVIER RIVER
Salina
WASATCH PLATEAU
Salina Creek
Area of Figure 8
Area of Figure 6
FISH LAKE PLATEAU
Fish Lake
SEVIER CO.
PIUTE CO.
WAYNE CO.
FREMONT R
Otter Creek
THOUSAND LAKE MOUNTAIN
Area of Figure 9
Bicknell
Area of Figure 7
AWAPA PLATEAU
BOULDER MOUNTAIN
GARFIELD CO.
AQUARIUS PLATEAU
Area of Figure 3
Area of Figure 4
TABLE CLIFF PLATEAU
ESCALANTE R
Escalante
Area of Figure 5
0 5 10 MILES
UTAH
GARFIELD CO.
KANE CO.
Henrieville

Figure 1.

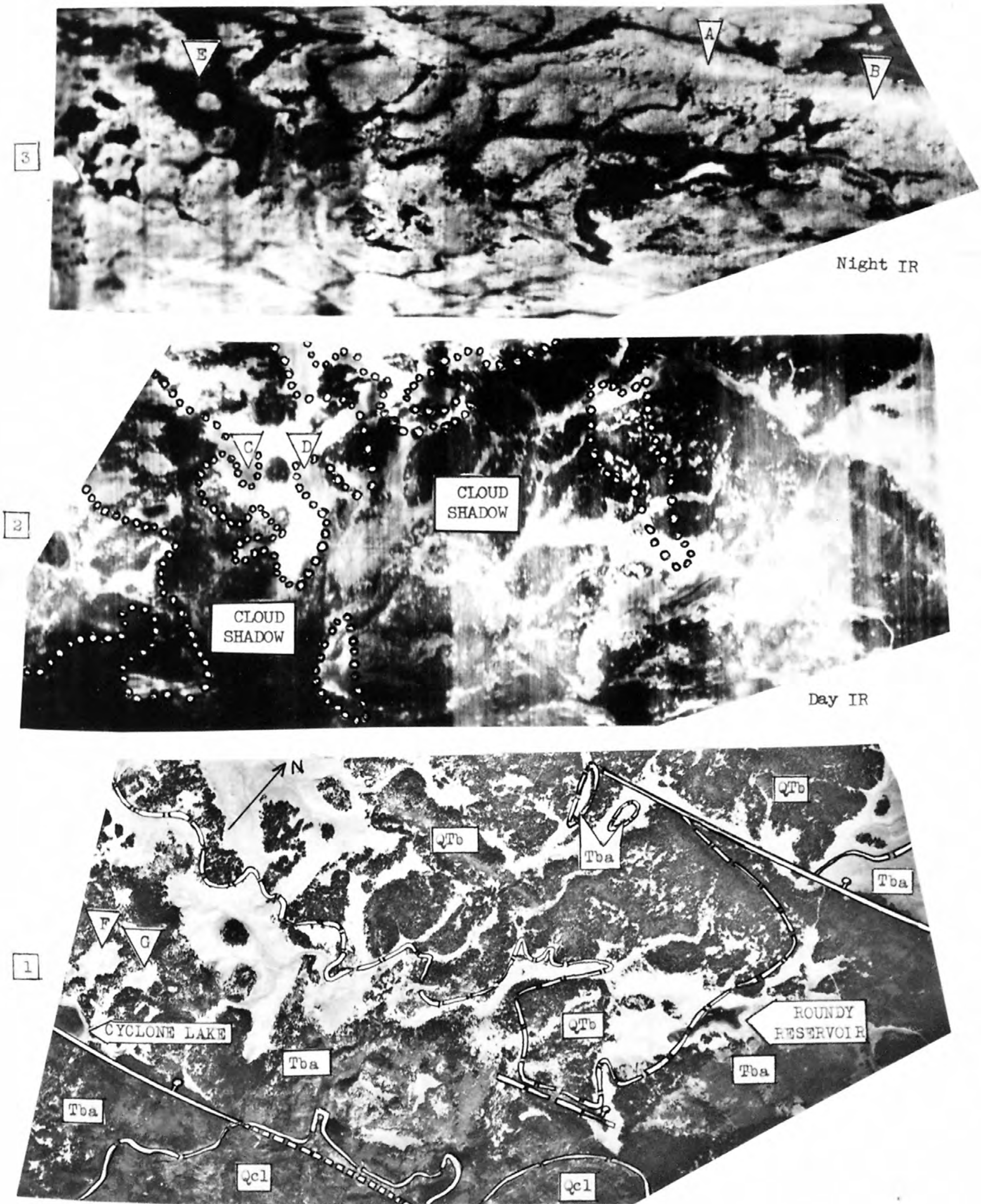
Figure 2. Graph showing the dirunal changes in soil temperature in bare and grass-covered soils. With both soils, the atmosphere becomes warmer than the surface at about 5 A.M. From that time until about midnight temperature varies considerably. Solar heat soon raises the temperature of the bare soil to a point higher than that of the atmosphere. The higher temperature differential of the surface of bare soil is present through the day and night with the exception of a short time in the early morning (5 A.M. to 8 A.M.) As long as the temperature of the soil is higher than that of the atmosphere, there is a flow of heat from the surface of the soil into the air. The grass covered soil, on the other hand, never becomes as warm as the atmosphere at any time during the day. Heat leaves the protected soil only between 11 P.M. and 5 A.M. The hachured bars show the time of day the infrared imagery used in this study was taken.



(Modified from Baver 1948, after Wollny)

Figure 2.

Figure 3.-- Alpine meadow and forest area on the Aquarius Plateau, southern Utah as shown by 1, annotated aerial photograph; 2, afternoon IR image; and 3, midnight IR image. The dotted line on afternoon IR image approximately outlines cloud shadowed areas identified on the color photography (not shown). The effect of the cloud shadow is an apparent reduction of surface temperature. This is especially noticeable in the open meadows such as at C and D. On the midnight IR brighter (warmer) areas in the meadow such as E are outcrops. F and G are two shallow ponds. On the midnight IR, both ponds have cooled to the temperature of the meadow, while the two larger bodies of water, Cyclone Lake and Roundy Reservoir, are still the brightest (warmest) features on the plateau. The brighter areas near the bottom of the midnight IR image are below the plateau and generally are south-facing slopes.



EXPLANATION

Qcl–Landslide detritus

QTb–Olivine basalt

Tba–Basaltic andesite

0 1 MILE

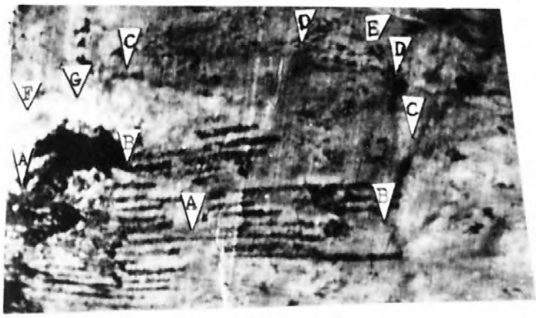
Fault

Dashed where approximately located, Dotted where concealed; bar and ball on downthrown side

Figure 3.

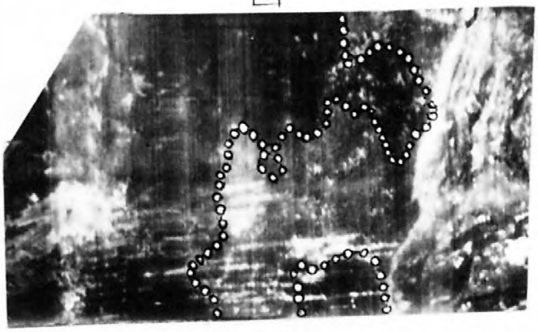
Figure 4.-- Area of a part of the Aquarius Plateau of southern Utah, as-shown by 1, aerial photograph; 2, afternoon IR image; 3, midnight IR image; and 4, geologic map. The prominent lineations, not visible on the aerial photograph are parallel logging swaths that were cut at a later date than that of the photograph. The less prominent lineations on the photograph and the night IR (A, B, C, D, and E) are the traces of faults shown on the geologic map. Most of these lineations are manifested by dark (cooler) tones and possibly are due to greater moisture content along the fault. The brighter (warmer) areas at F and G are steep, west-facing slopes, with considerable outcrop, and partly covered with aspen trees. Because afternoon radiation was more recent with respect to the time the IR image was made, these slopes are still warmer than adjacent forested areas and the darker (cooler) alpine meadow. The generally darker (cooler) outlined areas on the afternoon IR image are the result of cloud shadows identified on the color photography (not shown) which was taken at the same time.

3



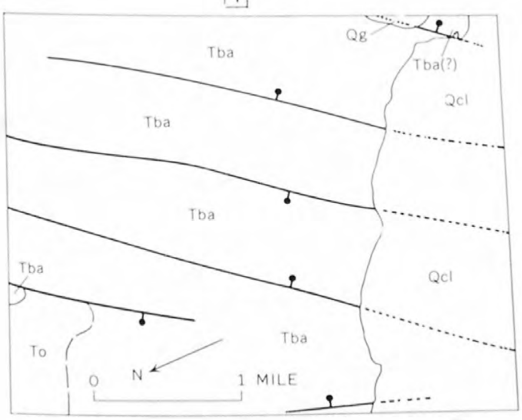
Night IR

2



Day IR

4



EXPLANATION

Qcl–Landslide and colluvial deposits

Qg–Glacial deposits

To–Tuff of Osiris

Tba–Basaltic andesite

Fault
Dotted where concealed, bar and ball on downthrown side

1

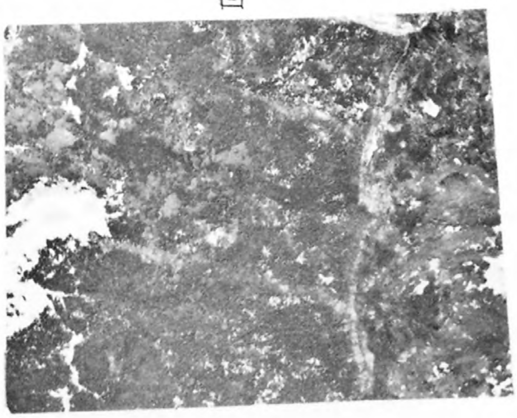
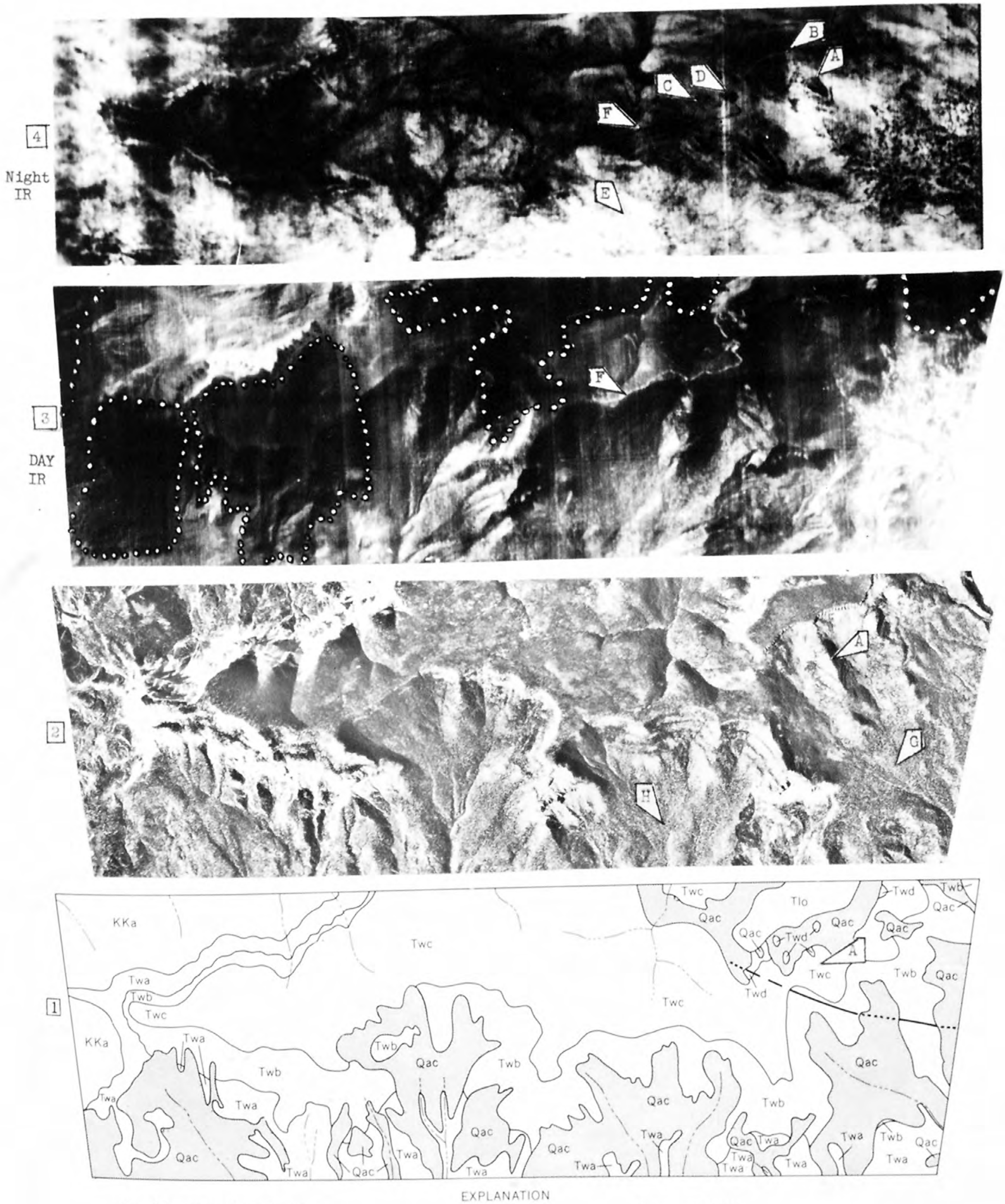


Figure 4.

Figure 5.-- Southern end of Table Cliff Plateau region of southern Utah, as shown by 1, geologic map; 2, aerial photograph; 3, afternoon IR image; and 4, midnight IR image. The darker (cooler) areas outlined on the day IR image were identified on the color photography (not shown) as cloud shadows. The greater part of the plateau is underlain by limestone (Twc) which appears generally darker (cooler) on the night image. The contact between the limestone and the underlying calcareous mudstones (Twb) is not sharp because of considerable talus present below the limestone cliffs. At A, however, on the night IR image the darker (cooler) limestone stands out in contrast to the overlying mudstones and sandstones (Twd) and the underlying calcareous mudstones (Teb). The brighter (warmer) band, B, at the base of the Tuff of Osiris may be a black vitrophyre or could also be caused by talus at the base of cliff formed by the Tuff of Osiris. The wooded area, C on top of the plateau is brighter (warmer) than the clearing, D, but not as bright (warm) as the wooded area, E, at a lower elevation. An access road, which can be recognized only in part in the stereoscopic model of the photograph is clearly visible at F on both the afternoon and midnight IR images. The two wooded areas, G and H, which have similar textual patterns on the photograph have noticeable dissimilar patterns on the IR images. Clearings in the wooded area G, resulting from recent logging operations, were identified on the color photography (not shown). The clearings are brighter (warmer) than the woods by afternoon and conversely darker (cooler) at midnight. Geologic map adapted in part from Bowers (1968).



EXPLANATION

Qac–Alluvium and/or colluvium
Tlo–Tuff of Osiris
Twd–Siltstone, mudstone, sandstone unit of Wasatch Formation
Twc–Limestone unit of Wasatch Formation
Twb–Calcareous mudstone and sandstone unit of Wasatch Formation
Twa–Sandstone–conglomerate unit of Wasatch Formation
KKa–Kaiparowits Formation

Fault
Dotted where concealed

N

0 1 MILE

Figure 5.

Figure 6.-- Area in and adjacent to Salina Canyon region of southern Utah as shown on 1, geologic map; 2, aerial photograph; and 3, midnight IR image. The brighter (warmer) areas on the midnight IR image are generally associated with the massive conglomerates and sandstones of the Price River Formation of Cretaceous age which stand out in contrast to the adjacent darker (cooler) thin sandstones and shales. This contrast is less apparent on north-facing slopes such as A, B and C which have received less solar radiation during the day and are consequently darker (cooler) at midnight. The delineation of the fault shown near the bottom of the geologic map, where the North Horn Formation of Cretaceous and Tertiary age is faulted down against older formations is recognizable on the night IR image. The darker (cooler) appearance of the North Horn Formation in this area and the similarly darker tone of the alluvium is probably due to a vegetation difference. These areas are sage brush and/or grass covered and cool faster than the wooded and outcrop areas. On the midnight IR image the brighter (warmer) line visible in Salina Canyon is a macadam surfaced highway; which is warmer than its surroundings at midnight. Geologic map modified after Spieker and others (1949).

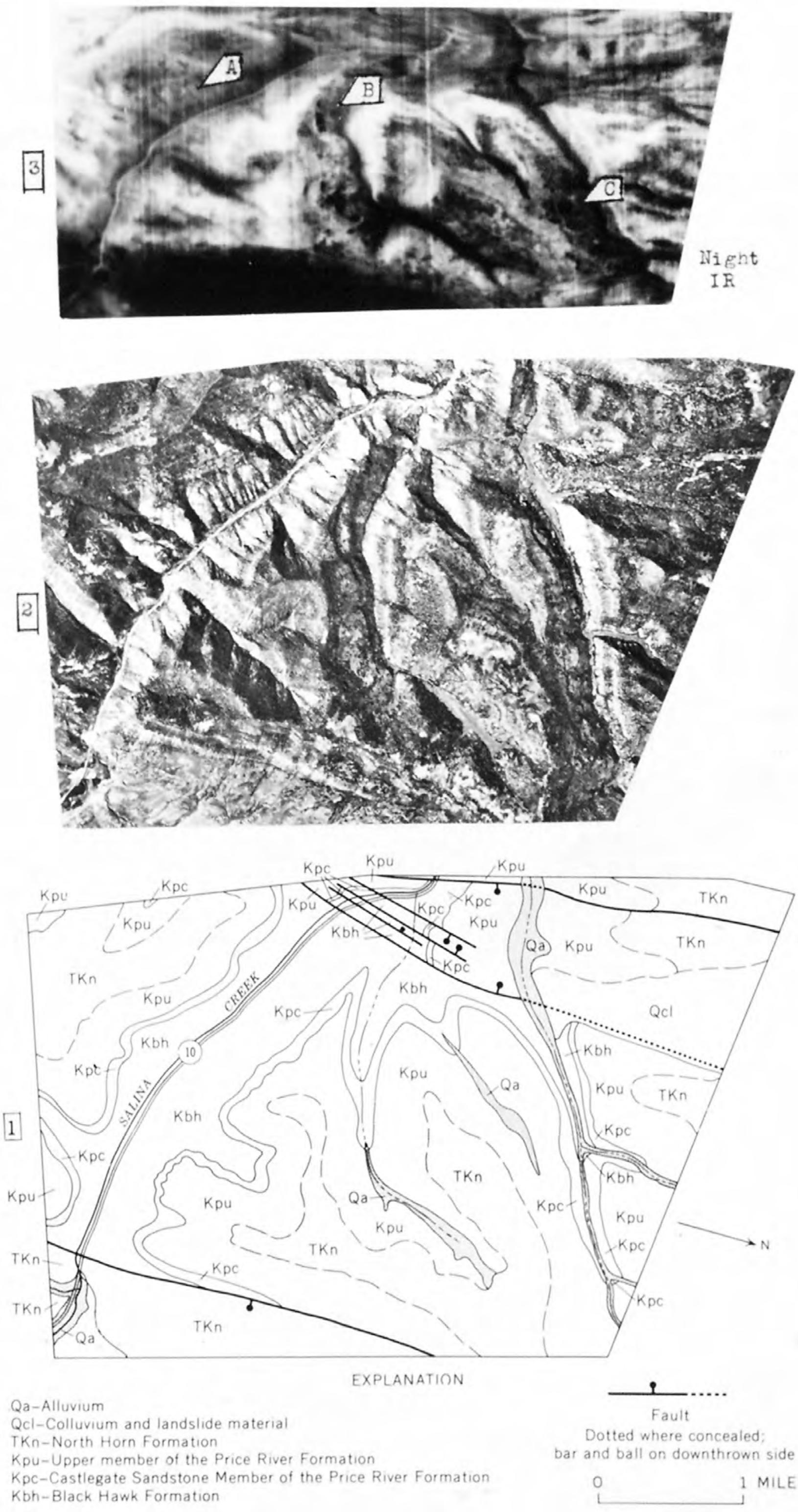

3
A
B
C
Night
IR
2
1
Kpc
Kpu
TKn
Kbh
Qa
Qcl
SALINA
CREEK
10
N
EXPLANATION
Qa–Alluvium
Qcl–Colluvium and landslide material
TKn–North Horn Formation
Kpu–Upper member of the Price River Formation
Kpc–Castlegate Sandstone Member of the Price River Formation
Kbh–Black Hawk Formation
Fault
Dotted where concealed;
bar and ball on downthrown side
0
1 MILE

Figure 6.

Figure 7.-- Area near Bicknell, Utah as shown on 1, geologic map; 2, aerial photograph; and 3, night IR image. The major sandstone units are generally defined as brighter (warmer) on the night IR. In the general area of A, B, and C, the bedrock is poorly exposed and mostly covered with volcanic boulders and slope wash. These west to southwest facing boulder covered slopes have been warmed by more recent solar radiation in the afternoon, and at midnight are still warmer (brighter) than some of the adjacent areas. The darker (cooler) area (bottom right - IR image) is probably due to ponding of cool air at night. The igneous rocks included in Tf and Ts stand out quite clearly because of their higher thermal inertia. Geologic map adapted from Smith and others (1963).

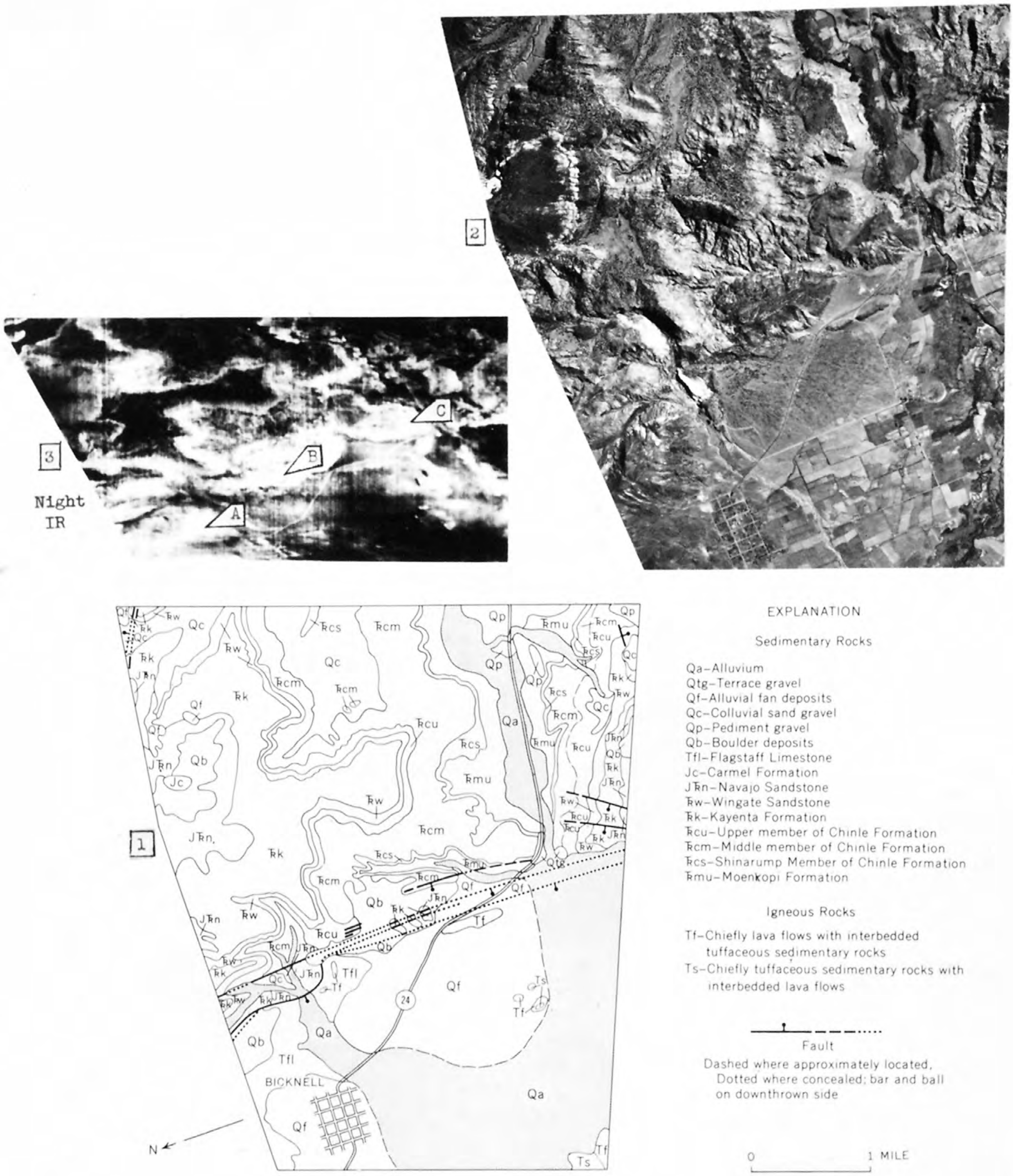
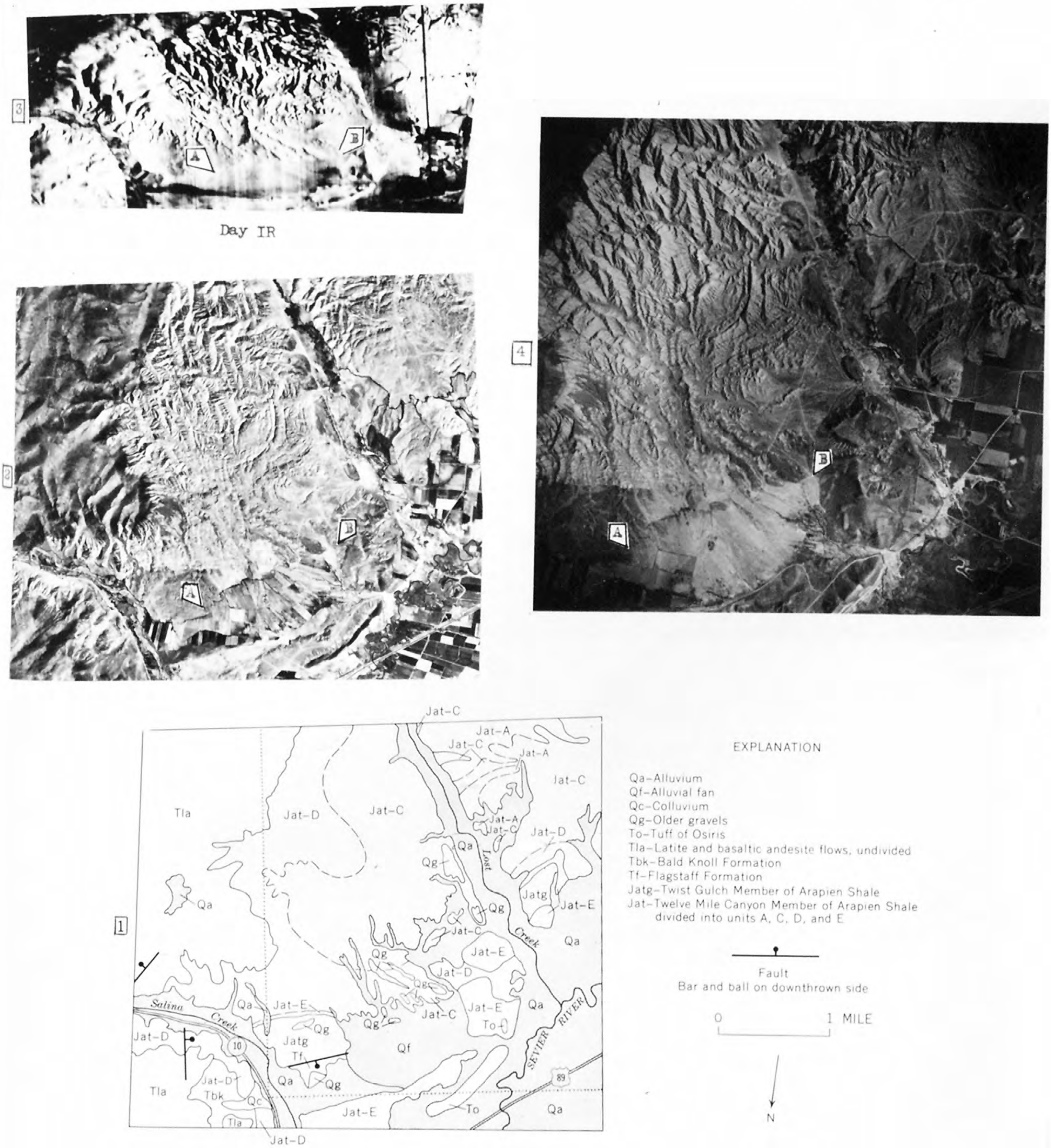

2
3
Night IR
A
B
C
1
BICKNELL
24
N
EXPLANATION
Sedimentary Rocks
Qa–Alluvium
Qtg–Terrace gravel
Qf–Alluvial fan deposits
Qc–Colluvial sand gravel
Qp–Pediment gravel
Qb–Boulder deposits
Tfl–Flagstaff Limestone
Jc–Carmel Formation
JTRn–Navajo Sandstone
TRw–Wingate Sandstone
TRk–Kayenta Formation
TRcu–Upper member of Chinle Formation
TRcm–Middle member of Chinle Formation
TRcs–Shinarump Member of Chinle Formation
TRmu–Moenkopi Formation
Igneous Rocks
Tf–Chiefly lava flows with interbedded tuffaceous sedimentary rocks
Ts–Chiefly tuffaceous sedimentary rocks with interbedded lava flows
Fault
Dashed where approximately located, Dotted where concealed; bar and ball on downthrown side
0
1 MILE

Figure 7.

Figure 8.-- Area near Salina, Utah as shown on 1, geologic map; 2, black and white photograph; 3, daytime (afternoon) IR image; and 4, black and white print of color photograph (color photograph covers only area indicated by dotted line on geologic map). The IR image shows a lineament, AB, which appears to be a continuation of the fault between Jatg and Tf, probably reflecting differences in surface texture and possible moisture content. However this IR image shows very little geologic information compared to the two photographs. Not even the obvious contact between the volcanic rocks and the sedimentary rocks is apparent. Based on color renditions alone, geologic information, most of which can be interpreted on the black and white photographs, is more readily and accurately obtained from the color photographs. Some geologic contacts are not recognizable on either the color or black and white film. Geologic map modified from Hardy (1952). Tonal differences, especially noticeable between the central part of 2 and 3 are due to color differences in the original color photographs which are not apparent on the black and white photographs.



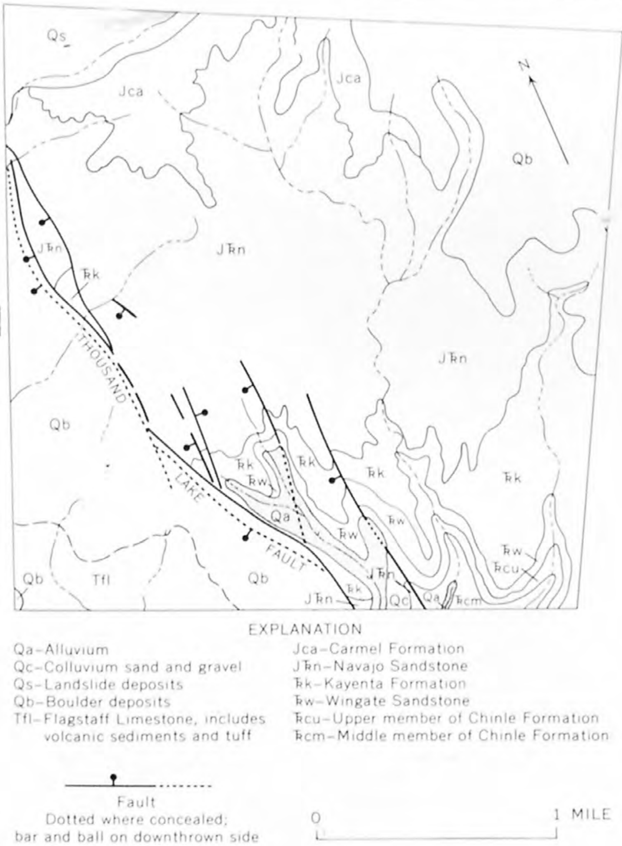
3
A
B
Day IR
2
A
B
4
A
B
1
Jat-C
Jat-A
Jat-D
Jat-E
Jatg
Tla
Qa
Qg
Qf
Qc
Tf
Tbk
To
Lost Creek
Salina Creek
SEVIER RIVER
10
89
EXPLANATION
Qa–Alluvium
Qf–Alluvial fan
Qc–Colluvium
Qg–Older gravels
To–Tuff of Osiris
Tla–Latite and basaltic andesite flows, undivided
Tbk–Bald Knoll Formation
Tf–Flagstaff Formation
Jatg–Twist Gulch Member of Arapien Shale
Jat–Twelve Mile Canyon Member of Arapien Shale divided into units A, C, D, and E
Fault
Bar and ball on downthrown side
0
1 MILE
N

Figure 8.

Figure 9.-- Area northeast of Bicknell, Utah as shown on 1, geologic map; 2, black and white photograph; and 3, black and white print of color photograph. Color differences between the lower half of the Navajo Sandstone (dark for red) and the upper half (white) is not apparent on the black and white aerial photograph, but is conspicuous on the print made from the color photograph. Color contrast is due to epigenetic bleaching of the upper part of formation. Geologic map adapted from Smith and others (1963)

3

1


Qs
Jca
Jca
N
Qb
JTRn
TRk
JTRn
JTRn
THOUSAND
LAKE
FAULT
Qb
TRk
TRw
TRk
TRk
TRk
Qa
TRw
TRw
TRw
TRcu
Qb
Tfl
Qb
JTRn
TRk
JTRn
Qc
Qa
TRcm
EXPLANATION
Qa–Alluvium
Qc–Colluvium sand and gravel
Qs–Landslide deposits
Qb–Boulder deposits
Tfl–Flagstaff Limestone, includes volcanic sediments and tuff
Jca–Carmel Formation
JTRn–Navajo Sandstone
TRk–Kayenta Formation
TRw–Wingate Sandstone
TRcu–Upper member of Chinle Formation
TRcm–Middle member of Chinle Formation
Fault
Dotted where concealed; bar and ball on downthrown side
0
1 MILE

2

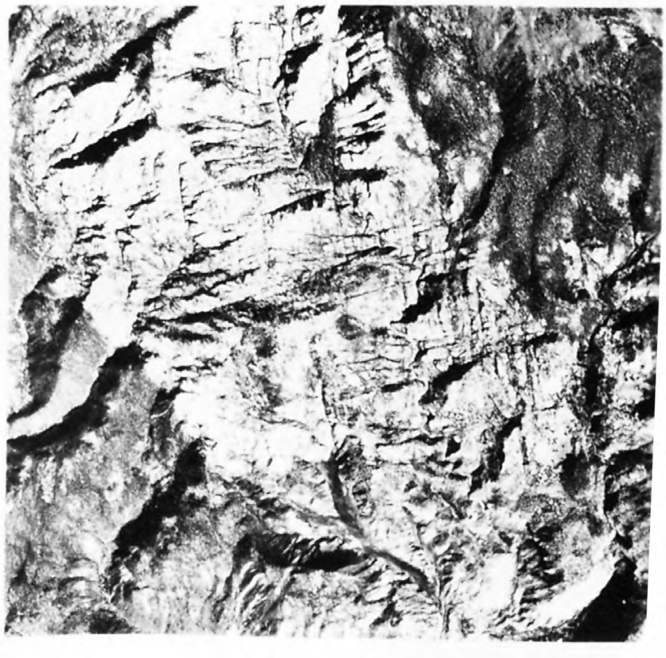


Figure 9.

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