Richard S. Williams, Jr.
U. S. Geological Survey
Reston, VA 22092
Philip G. Hasell, Jr.
Albert N. Sellman*
Environmental Research Institute of Michigan
Ann Arbor, MI 48107
Harry W. Smedes
U. S. Geological Survey
Denver, CO 80225

Thermographic Mosaic of Yellowstone National Park

Improved techniques in the preparation of thermographic mosaics will enable more widespread use of such mosaics in regional environmental studies.

Abstract: *An uncontrolled thermographic mosaic, which covers most of the area of Yellowstone National Park, has been compiled. The recording of aerial thermographic data on videotape is established as one of the prerequisites for the preparation of more accurate mosaics. Post-mission processing of the videotape record can rectify the nadir line to a topographic map base, correct for* v/h *variations in adjacent flight lines, correct for yaw distortions, rectify distortions caused by pitch, and rectify distortions produced by non-linearity of the side-wise scan. Installation of a thermal infrared scanning radiometer in a gyrostabilized mount and post-mission processing of the videotape record (principally rectification of side-wise scan distortion) would yield a controlled, photogrammetrically accurate thermographic mosaic. However, the techniques used in the preparation of the uncontrolled thermographic mosaic of Yellowstone National Park can be immediately applied to the preparation of regional thermographic mosaics, important to geologists and other scientists and engineers in studies of geothermal and volcanic areas, and to other types of environmental investigations such as pollution studies of large water bodies (e.g., harbors, estuaries, lakes, etc.), where a precise planimetric image is not critical.*

Introduction

During the month of April 1969, the U. S. Geological Survey (EROS Program Office), Air Force Cambridge Research Laboratories (Terrestrial Sciences Laboratory), and the University of Michigan's Institute of Science and Technology (Infrared and Optics Laboratory** teamed up to create the first aerial thermographic mosaic of Yellowstone National Park. The aerial thermography was acquired by the M1A1 scanner (Fisher *et al.* 1965) mounted in a U. S. Air Force (AFCRL) JC-130A/D "Hercules" aircraft with scanner operation by University of Michigan personnel. The survey was carried

* Presently with the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD 20771.

** Now a component of the Environmental Research Institute of Michigan.

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out during the night of 9-10 April 1969, at an altitude of approximately 8,200 m (27,000 feet), and required nearly 5 hours to complete.

SURVEY OBJECTIVES

There were four primary reasons for the aerial thermographic survey. First, a thermographic mosaic of Yellowstone National Park would be useful to geological and geophysical investigations by delineating the areas of thermal emission (from hot springs, geysers, etc.) throughout the Park during a specific period in time. Second, the M1A1 scanner had been modified for videotape recording (Miller and Roe, 1967); hence, post-survey rectification of the aerial thermography was possible. Third, the service ceiling of the C-130 aircraft [over 9,100 m (30,000 feet)] permitted a high-altitude aerial thermographic survey of a geothermal area to be carried out—of great value in reconnaissance surveys of geothermal areas in remote areas or in areas of high relief. Finally, the thermographic mosaic would complement the previously published radar mosaic*, the color aerial photographic mosaic (Smedes, unpublished data**), the Geologic Map of Yellowstone National Park (USGS, 1972a), and the Surficial Geologic Map of Yellowstone National Park (USGS, 1972b). Since the aerial thermographic survey was compted, ERTS-1 (Landsat-1) imagery of Yellowstone National Park has also become available. A fall image (1123-17414) and a summer image (1015-17404) provide excellent views of the area and are useful for correlating features visible on the thermographic mosaic. For example, resolution of the Landsat imagery (~80 m) is sufficient to show the hot spring deposits in the Lower Geyser Basin, an area of intense thermal emission on the thermographic mosaic.

PREVIOUS SURVEYS

At least four previous aerial thermographic surveys have been made of parts of Yellowstone National Park, beginning in 1961 (Table 1).

These aerial thermographic surveys and the associated aerial photographic surveys have provided the data for several geological and geophysical investigations. McLerran and Morgan (1965) published the first paper on aerial thermographic studies in the Park. White and others (1968) briefly discussed their geophysical research on the geothermal areas in the Park for eventual correlation with aircraft remote sensor data; of particular interest to aerial thermographic studies is their discussion of snowfall calorimetry. White and Miller (1969) and White (1969) pursued this latter work in mapping of low-intensity geothermal anomalies in the Park. Christiansen (1968) has studied the mapping of bedrock and unconsolidated deposits from aerial thermography (3-5 μm) of the rhyolite plateau of Yellowstone. Of particular interest was Smedes' (1968) evaluation of aerial thermography in the eastern and north-central parts of the Park to study areas underlain by early Cenozoic volcanic rocks. Smedes (1970) also studied enhancement techniques with various types of photography and imagery, including aerial thermography. Waldrop (1969) studied the detection of thick surficial deposits from aerial thermography (8- 14 μm) of the northwestern part of the Park. Pierce (1968) published an evaluation of aerial thermography (3-5 μm) to studies of surficial geology in Yellowstone. Smedes (1971) used data from two thermal infrared scanners combined with multi-spectral scanner data to evaluate usefulness of aerial thermography and multi-spectral imagery alone in compiling maps of terrain classes with computer-assisted techniques.

Along with aerial thermographic remote sensing studies of geothermal areas, regional geologic studies involving remote sensing were also pursued (Smedes, 1969). Several radar studies have been carried out beginning with Christiansen and others' (1966) preliminary analysis of radar imagery of Yellowstone. Prostka (1970) published a geologic analysis of the radar mosaic of the entire Park. Richmond (1970) studied the geologic significance of anomalies recorded on like- and cross-polarized, k-band, radar imagery of Yellowstone. Keefer (1968) evaluated the radar and infrared imagery of sedimentary rocks in south-central Yellowstone. In addition, conventional geologic mapping (bedrock and surficial geology) was also carried out in the Park (U.S. Geological Survey, 1972a and 1972b), partly in support of the airborne remote sensing studies and for use with imagery from the Landsat-1 satellite. Smedes (1976) has recently

* The Radar Mosaic (uncontrolled) of Yellowstone National Park (1968) is available from the EROS Data Center, Sioux Falls, South Dakota 57198 by reference to accession no. E-16-2430BN.

** Copies of the color aerial photographic mosaic are available from the EROS Data Center, Sioux Falls, South Dakota 57198, by reference to accession no. E-415-45CT.

TABLE 1. KNOWN AERIAL THERMOGRAPHIC SURVEYS OF YELLOWSTONE NATIONAL PARK.

Areas Surveyed	Date(s) of Survey	Organizations Involved	Type of Scanning Radiometer
Selected Areas	20-22 Apr. 61	Univ. of Mich./ U.S. Army Cold Regions Research and Engineering Lab.	HRB-Singer D2
Most of Park	13-15 Aug. 66	U.S. Geol. Survey/HRB Singer, Inc.	RECONOFAX IV
Selected Areas	20-21 Sept. 66	U.S. Geol. Survey/HRB Singer, Inc.	RECONOFAX IV
Geyser Basins and Parts of Yellowstone Lake, Yellowstone River, and Lamar River	19-22 Sept. 67	U.S. Geol. Survey/Univ. of Michigan	M5 Multispectral
Most of Park	9-10 Apr. 69	Air Force Cambridge Res. Labs./U.S. Geol. Survey/ Univ. of Michigan	M1A1

completed a land-use planning study of the Park from Landsat-1 imagery.

AERIAL THERMOGRAPHIC MOSAICS

Generally speaking, the interpretation of aerial thermography (Williams, 1972) in geological investigations is easier to accomplish and is more comprehensive if the individual thermographs can be compiled into an areal "map" or mosaic (Williams and Ory, 1967). This is because many types of geological phenomena encompass areas larger than can be imaged on a single thermograph (or photograph, for that matter) (Stingelin, 1969). Since the output of most current scanning devices for producing aerial thermographs are "strip maps" which are subject to geometric distortion, the compilation of a geometrically accurate thermographic mosaic is a difficult task. The thermographic mosaic of Yellowstone National Park is presented as a typical mosaic made from separate film strips produced in 13 successive passes over the area. A few aspects of the geologic information recorded on the thermographic mosaic are described along with its imperfections and the sources of the imperfections.

THERMOGRAPHIC MOSAIC

Figure 1* is the completed mosaic, covering approximately 3,000 square miles (7,770 km^2) or about 85 per cent of the area of Yellowstone National Park. In three instances there was insufficient side-lap to yield a complete coverage mosaic, thereby producing gaps in the coverage. The east-west dimension is quite close to scale while the north-south dimension is "stretched" by approximately 9 per cent. Additional processing could minimize this latter distortion.

The mean survey time was just after midnight (0022 hours) on 9-10 April 1969, and except for minor cloud cover over the southwest end of Shoshone Lake and over the southeast arm of Yellowstone Lake, the mosaic discloses the unobscured surface topography and hydrographic systems quite well. The relatively high water temperatures associated with thermal activity display springs, rivers, and lakes as distinct "white" targets on the black-and-white mosaic.

The mosaic was constructed from film images produced by playback of the scanner data recorded on magnetic tape during the flight. The tape signals are used to intensity-modulate a cathode ray tube (CRT) sweep-signal which exposes strip film. The CRT sweep and the drive speed of the film strip are correlated with the airborne line-scan rate, the aircraft ground speed, and the flight altitude above terrain to provide proper image scaling onto the film. The resulting film strip is a negative transparency from which a positive paper print is made for assembly into the mosaic.

Ideally the strips will have sufficient side-lap to allow only the center portion of each line to be used in the mosaic, where "across-track" distortion is at a minimum (Williams and Ory, 1967). The "along-track"

* The Thermographic Mosaic of Yellowstone National Park, Wyoming, Idaho, and Montana, is available from the EROS Data Center, Sioux Falls, South Dakota 57198 by reference to accession no. E-17-2235BN.

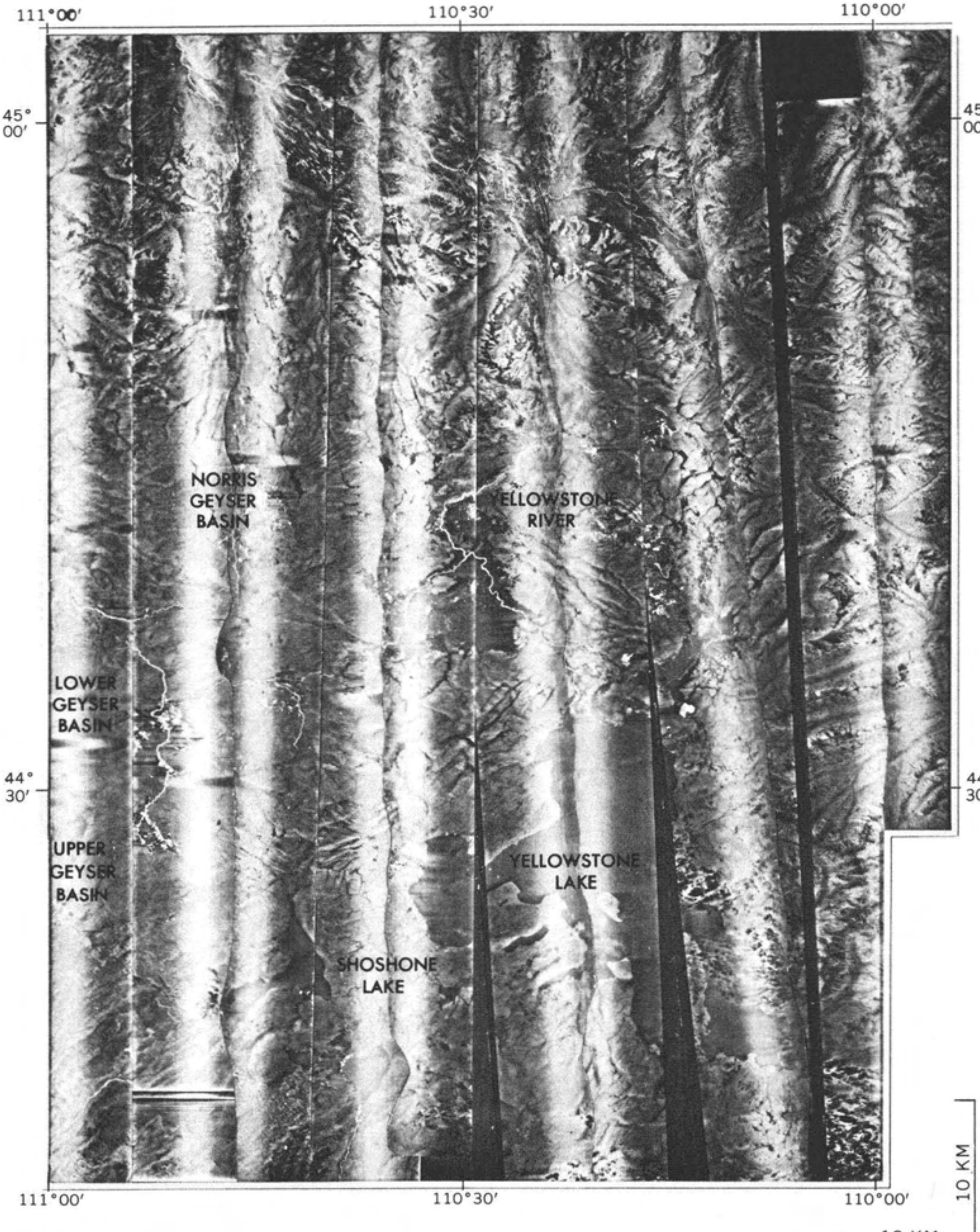

FIG. 1. Aerial thermographic mosaic of Yellowstone National Park, Wyoming, Idaho, Montana. Mosaic was assembled from the videotape record of 13 individual thermographs. [9-10 April 1969, 0022 hrs. (mid-point of 4 hrs. 48 min. survey), 27,000 ft. (8,200 m) alt. or 18,000 ft. (5,500 m) above ave. terrain), inSb (unfiltered), approximate original scale, 1:180,000]. Air Force Cambridge Research Laboratories thermograph.

and "across-track" scaling should be equivalent. Since the instrument normally has a fixed "across-track" field-of-view (FOV), the "across-track" scaling is a direct function of altitude. The "along-track" scaling is dependent upon both altitude above terrain and the aircraft velocity relative to the ground track.

Fortunately, variations in "along-track" and "across-track" scaling can be corrected during film strip reproduction from tape playback. Figure 2 shows sections of two strips of the same flight line over Turbid Lake, located to the right-of-center in the full mosaic. These illustrate, in part, the capability of "along-track" scaling corrections during tape playback. Strip A is a print of the first film strip produced from the flight tape

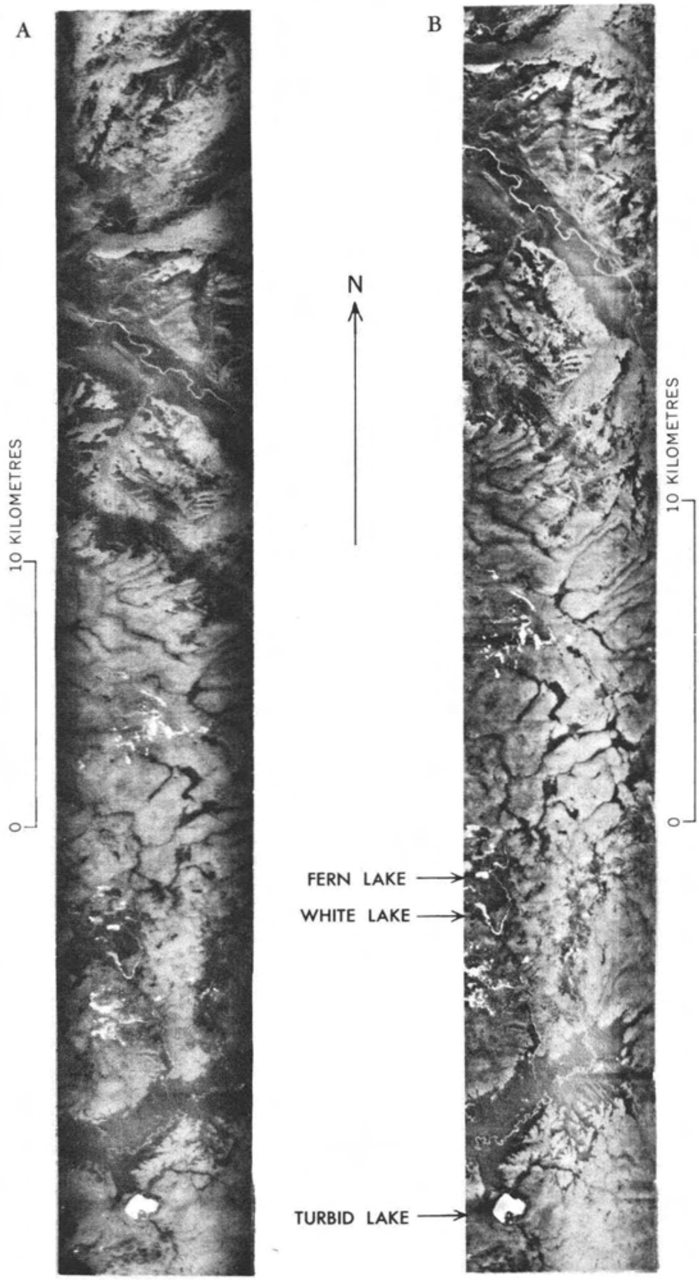

FIG. 2. Aerial thermographs of the Turbid Lake area (kidney-shaped lake north of Yellowstone Lake and east of Yellowstone River), Yellowstone National Park, Wyoming, showing original playback of videotape record (A) [original nadir line scale, approx. 1:340,000] and "stretched" playback of videotape record (B) [original nadir line scale, approx. 1:282,000]; [10 April 1969, 0030 hrs., 27,000 ft. (8,200 m) alt., InSb (unfiltered)]; Air Force Cambridge Research Laboratories thermograph.

by using flight-recorded aircraft altitude and ground speed. Strip B is the second print "stretched" to conform to the mosaic scale as determined by recognition of terrain features. Strip B was produced by increasing the speed at which the film passes in front of the modulated CRT sweep signal, producing a longer film strip for the same time period of tape data. Thus, on a trial and error basis, each strip length could be increased or decreased to fit a uniform scale. Of course, when both the aircraft altitude above terrain and ground speed are known accurately in the first place, the scaling can be adjusted properly in the initial playback. Herein lies the major limitation in using line-scan devices to create mosaic area maps—the precise location on the terrain surface and direction and rate of scan motion of the instantaneous small FOV of the line scanner is difficult to determine. Once this information is known, however, it is relatively easy to produce accurate scaling in film strip reproductions. Conventional aerial photography does not have this same limitation because, in effect, the film is made up of many small detectors which register a large area of terrain in the same instant. Variations in aircraft altitude will result in photos of different scale; scale may vary within a photo, depending on local relief. Inaccuracies in aircraft altitude, attitude, and ground speed also affect the amount of overlap between successive frames. In compiling aerial photographic mosaics, however, side-lap fitting of adjacent frames can pose a problem because of radial distortion of terrain features when photographed from a different camera position.

General Distribution of Geothermal Emission

Figure 3 (modified from Figure 5 in Waring, 1965, p. 15) is a sketch map of Yellowstone National Park showing geographic features and the location of principal thermal springs, geysers, and mud pools. (For additional general information of the geology and geothermal areas of the Park, see the excellent booklet by Keefer, 1971.) The scale of Waring's map (Figure 3) is equal to that of the thermographic mosaic (Figure 1); hence, the information content can be readily compared. Considerable hydrogeologic, particularly geothermal, information has been recorded on the aerial thermography. Unfortunately, essentially no direct surficial (USGS, 1972b) or bedrock (USGS, 1972a) geologic information is provided because of the deep snow which mantled the Park at the time of the survey—early April 1969. However, the extent and nature of the structural control of bedrock on topography, particularly on the geometry of the drainage pattern, are well shown.

Many of the prominent physiographic features of the Park can be delineated on the thermographic mosaic because of distinct topographic expression and drainage texture. For example, the texture of erosional dissection of the Absaroka Range (Eocene volcanics) is markedly different from that of the other mountain areas. The rhyolite plateau, extending roughly from the Yellowstone River southwest to beyond Upper Geyser Basin and Shoshone Lake, and the main central lowlands can be distinguished.

The young faults and fracture patterns in the Amethyst Mountain area and those due to resurgent doming of the caldera floors in the area between Elephant Back Mountain and northwest of Sulphur Hills and in the Mallard Lake area east of Upper Geyser Basin are clearly shown. These faults and fractures are shown on the geologic map (U.S. Geological Survey, 1972a), but analysis of the thermographic mosaic suggests that more faults exist than were mapped in the area northwest of the West Thumb Geyser Basin, thereby forming a linkage between the Elephant Back Mountain and Mallard Lake areas.

The arcuate flow-folds of the rhyolitic lavas in the southwest corner of the thermographic mosaic (Bechler River area) are prominent. Glacially-scoured arcuate northwest-trending grooves and ridges on Mount Everts are visible. The northwest-trending fault scarp complex north of Gardiner, and the sedimentary layers on Cinnabar Mountain (northern edge of the thermographic mosaic) are extremely clear.

The north-south-trending faults of Mount Sepulcher can be delineated. Northerly-tending faults of the Mount Washburn area are generally well shown. Those faults to the west, but to the east of Roaring Mountain and Norris Geyser Basin, are less prominent than a probable northeast-trending set of faults which is strongly suggested by the thermographic mosaic. This latter set of faults does not appear on geologic maps.

It is important to note that some geological information was lost in the specially-processed thermographs used to compile the mosaic when compared with the direct-record thermographs. The direct-record thermographs seemed to have higher detail in many areas and, in some cases, surveyed a slightly different area. Ice-fracture patterns were visible on the direct-record thermo-

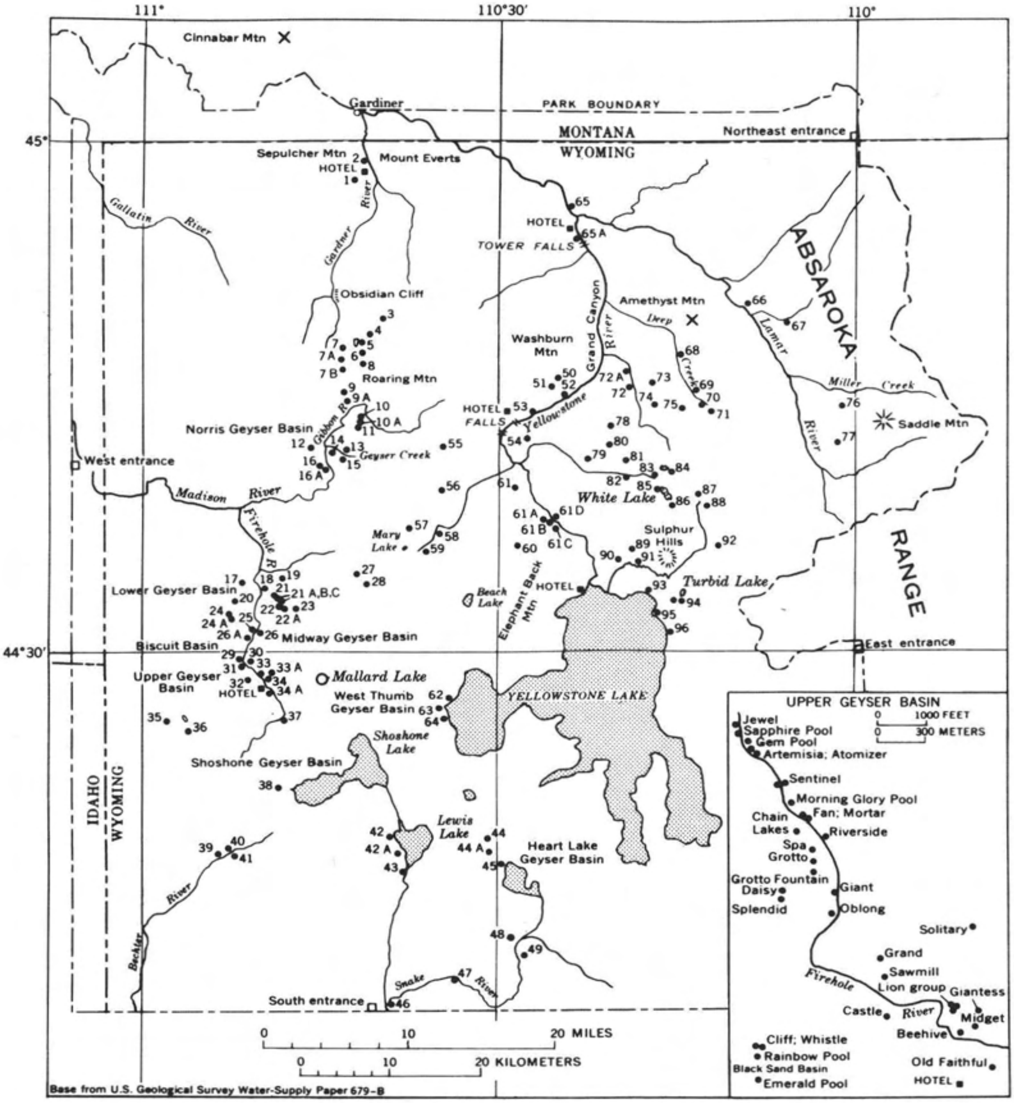

FIG. 3. Sketch map of Yellowstone National Park showing geographic features and principal areas of hot springs. (Modified from Figure 5 in Waring, 1965, p. 15.) (Original scale of Waring sketch map is 1:750,000.)

graphs, but not on the specially-processed thermographs. This variation in thermographs is probably the result of different electronic settings for each version. After all, the primary objective was to produce a thermographic mosaic of a large area, not to optimize the thermographic mosaic for geologic information. With appropriate electronic settings, the thermograph used to compile the thermographic mosaics could be made similar to the direct-record thermographs.

From a geological viewpoint, the survey altitude was far higher (8,200 m a.m.s.l.) than is usual for such surveys, although similar survey altitudes were employed during the aerial thermographic surveys of Iceland (Friedman *et al.* 1969). The flying altitude was necessary not only to complete the survey in one mission but also to provide a synoptic or regional display of geothermal activity—as opposed to low-altitude surveys of a local geothermal area. Of course, the "resolution" possible from such a survey altitude prevents the depiction of very small geothermal features in an area of intense geothermal activity (e.g., Lower Geyser Basin). Many separate points (e.g., mudpots, geysers) or areas (e.g., steaming ground) of geothermal activity merge into a diffuse area of geothermal emission.

Because of the snow cover and the frozen lakes, geothermal areas and areas affected by discharge of hot water (e.g., streams and lakes) stand out sharply on the aerial thermographic mosaic as areas of white tone. Near the bottom of Figure 2, Turbid Lake is shown as ice-free, the result of hot springs discharging into the lake from the south, or possibly caused by submarine hot spring activity. Tern Lake to the north appears to have ice on the southern margin of the west lobe of the lake but is ice-free to the north. An area of intense geothermal emission is shown south of White Lake, although it is not cited by Waring (1965) or depicted on either the 1:125,000 (USGS, 1961) or 1:62,500 (USGS, 1959) topographic maps of the area; however Smedes (1968) plotted its position on Figures 10 and 12 of that report. The Hot Spring Basin Group in the center of the thermograph (Figure 2) is well delineated, but again neither the sketch map (Figure 3) nor the 1:125,000 topographic map shows the full extent of the geothermal area, particularly its southwestern extent to the west of Shallow Creek (Canyon Village, 15-minute Quadrangle Map, 1959).

From a qualitative viewpoint, the largest area of intense thermal emission on the entire thermograph is the area north of Yellowstone Lake, an area of hot springs on the southern part of Sulphur Hills. The main hot springs areas, such as Upper and Lower Geyser Basins, Norris Geyser Basin, etc., are well delineated by the distribution of numerous points of thermal emission and large areas of warm or steaming ground. Several points of thermal emission are qualitatively "hot" compared to other areas in the Park.

Of interest in hydrogeological studies are the tonal changes which take place along the courses of the many rivers and streams in Yellowstone National Park. Firehole River, which traverses both the Upper and Lower Geyser Basins to the confluence of the Gibbon and the Madison Rivers, and Yellowstone River are excellent examples. Yellowstone River shows a marked tonal change along its course to Yellowstone Lake. The reason for the tonal changes is the addition of warm (or hot) water to the rivers or streams from surface runoff from hot springs or from warm groundwater discharging into streams and rivers.

Finally, there are many points or areas of thermal emission shown on the thermographic mosaic which are not shown on either the 1:125,000 or 1:62,500 scale maps. Examples of this, besides the areas previously noted, are hot springs discharging into the southern shore of Shoshone Lake (to the left of the mouth of Moose Creek) and on the north shore of Lewis Lake, just west of the mouth of Lewis River.

Conclusions

Considerations for Thermographs

To produce useful thermographs from line-scan devices, the following provisions must be made in the production of imagery:

(1) Either the line-scan device must be stabilized about three axes in the aircraft or the instrument motion about these axes must be recorded on tape along with the video signal for stabilization of imagery during film strip reproduction. Traditionally, as in the Yellowstone mosaic, only motion about the aircraft roll axis is accounted for in imagery reproduction, but stabilization about the other two axes is also relatively easy to accomplish.

(2) The average aircraft altitude above terrain and in particular the aircraft ground track and speed must be known accurately both to fly the mission and to reproduce the data. Otherwise, insufficient overlap will exist between successive flight lines and the scaling will be inaccurate. In the absence of accurate navigational systems in the aircraft, ground markers at known locations can be used to guide the aircraft and to scale the imagery.

(3) The imagery must be rectified in the film reproduction to correct for the varying path length between the aircraft and the terrain surface along the scan line. This rectilinearization amounts to producing an appropriately nonlinear scan rate either in the scanning device or in the sweep of the CTR printer. This type of imagery distortion was not removed from the Yellowstone mosaic and is usually minimized by using only the central portion of the strip imagery, where the distortion is minimal.

(4) The radiation response of the line-scan device must be constant as a function of scan angle. It is preferable that the response be the same throughout the scan, but at least it must be constant and known so that it can be accounted for in the film strip reproduction. The scanner response was neither known nor accounted for in the reproduction. In this particular imagery this radiation distortion appears as an average film tone change a-

cross the film strip, commonly referred to as "humping" of the signal. More sophisticated electronic processing techniques could minimize this undesirable tone variation within each of the image strips.

RECOMMENDATIONS

It is interesting to note that with relatively minor modifications and additions to line-scan devices, they can be used to produce thermographs relatively free of geometric distortion. Electronic modifications to improve image quality amount to: (1) removing sources of stray radiation from the line-scan devices so as to establish their predictable response as a function of scan angle; and (2) restoring the low-frequency components of the video signal for recording on magnetic tape. Geometric improvement in the images can be attained by the provision of a three-axis stabilized reference source on the scanning device and recording the motion about these axes on magnetic tape along with the video signal and scanner synchronization. This information can then be used in a film strip printer to produce distortion-free images. With proper provisions, the CRT sweep can correct for aircraft motion and rectilinearization of the imagery. The CRT intensity control can correct for non-linearities in response as a function of scan angle. The film drive for the film-strip printer can be correlated with aircraft altitude and ground speed to produce image scaling. These provisions are all technically feasible, but they are not being done because of the infrequent demand at present for mosaic maps made up from line-scan imagery. However, without bothering to remove any image distortion, useful thermographs can be produced from line-scan devices if patience and skill are used on a trial-and-error basis to fit the images into a mosaic.

From a scientific viewpoint, rectified thermographic mosaics can provide valuable information to geologists, because a mosaic shows the relative size and qualitative thermal emission from geothermal areas. In the case of Yellowstone National Park, the topographic map shows "size" of geothermal area only in a schematic way by distribution and number of small blue circles and by printing the names of the springs in different style and size of type face. When depicting hot springs on a topographic map, consideration should be given to overprinting the map with a specific color to show actual areas of geothermal emission. The distribution and occurrence of hot springs are depicted on aerial thermographs. Such data could be used as a source of information in compiling maps of geothermal areas.

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