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**THERMAL SURVEILLANCE OF CASCADE RANGE VOLCANOES USING
ERTS-1 MULTISPECTRAL SCANNER, AIRCRAFT IMAGING SYSTEMS, AND
GROUND-BASED DATA COMMUNICATION PLATFORMS***

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ABSTRACT

A combination of infrared images depicting areas of thermal emission and ground calibration points have proved to be particularly useful in plotting time-dependent changes in surface temperatures and radiance and in delimiting areas of predominantly convective heat flow to the earth's surface in the Cascade Range and on Surtsey Volcano, Iceland. In an integrated experiment group using ERTS-I Multispectral Scanner (MSS) and aircraft infrared imaging systems in conjunction with multiple thermistor arrays, volcano surface temperatures are relayed daily to Washington via Data Communication Platform (DCP) transmitters and ERTS-I. Estimates of the magnitude of radiative and convective heat flow at several surface thermal manifestations in Lassen Volcanic National Park are providing data on the energy yield at the earth's surface during Lassen's current period of repose. Repetitive aircraft infrared imaging missions have recorded the outgoing radiative flux from the terrestrial surface, which has been essential in locating, delimiting and recording changes in surface thermal anomalies at Lassen, Mt. Rainier, Mt. St. Helens, Mt. Baker, Mt. Shasta and Mt. Hood. ERTS-I MSS imagery has revealed curvilinear structures at Lassen, the full extent of which have not been previously mapped. Interestingly, the major surface thermal manifestations at Lassen are aligned along these structures, particularly in the Warner Valley. On Lassen Peak, and possibly at Mt. St. Helens, smaller thermal anomalies are controlled by the contact margins of silicic or intermediate extrusive plugs, and particularly at Lassen, may mark a line of structural weakness along Manzanita Creek Valley.

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1. INTRODUCTION AND BACKGROUND

In regions of active volcanism, during periods of repose of active volcanoes as well as during periods of eruption, a sizable heat flux reaches the surface by mass transfer. At Wairakei in New Zealand, Robertson and Dawson (1964, p. 134) have shown that in at least the Wairakei environment, conduction is the dominant mechanism of transfer when the difference between the surface temperature and that at 100 cm depth is less than 25°C. Where the temperature at 100 cm exceeds 25°C, convective transfer becomes the dominant mechanism. This transition corresponds to a heat flux of about $50 \mu\text{cal cm}^{-2} \text{sec}^{-1}$ (2.09×10^{-4} joules $\text{cm}^{-2} \text{sec}^{-1}$), or 33 times the mean terrestrial flux. The capability of airborne optical-mechanical infrared line-scan systems to distinguish and record changes in surface thermal anomalies corresponds to a flux of about $200 \mu\text{cal cm}^{-2} \text{sec}^{-1}$ (Palmason et al., 1970, p. 404) well within the range of predominantly convective transfer.

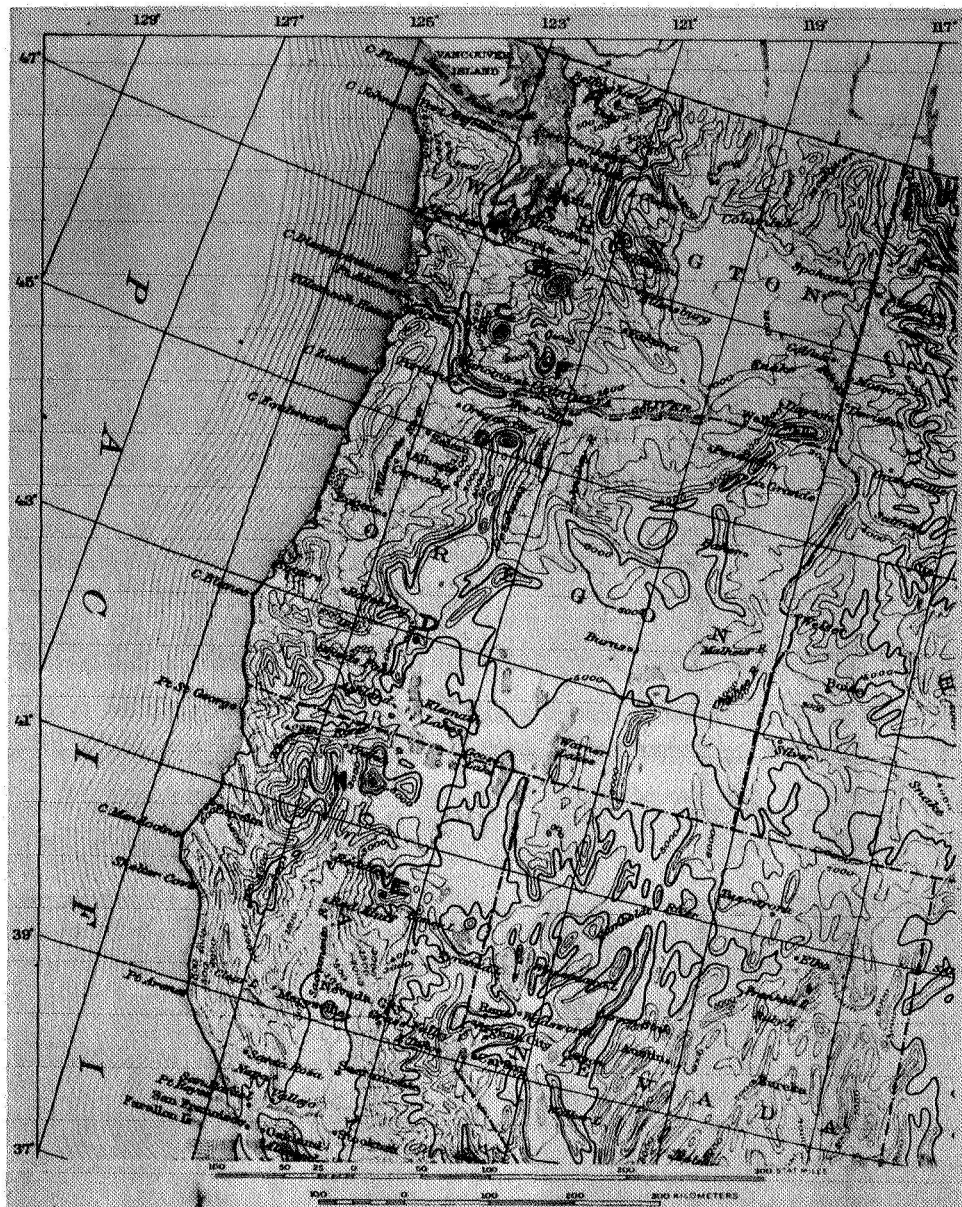
An increase in convective heat flow prior to volcanic outbreaks within areas of volcanic thermal anomalies has been documented at a number of volcanoes (Moxham, 1971, p. 103-105) including Askja, Taal, Kliuchevskoi, Surtsey, and others. The study of repose-period energy yield and of the circumstances under which thermal forerunners can be used as a predictive clue to impending volcanic activity are the subjects of this report.

It is known that vapor emission associated with convective transfer also fluctuates as a result of changes in barometric pressure and precipitation aside from that resulting from forerunning volcanic thermal emission. Consequently, systematic continuous temperature observations at a number of volcanic fumaroles by ground-based thermistor-probe recording or transmission systems, and synoptic airborne infrared line-scan surveys, are important in providing the essential geophysical data for significant thermal emission studies of volcanic systems.

The ERTS-I Data Communication System has been used in conjunction with Geological Survey-Forest Service and Manned Spacecraft Center aircraft infrared surveys of several Cascade Range volcanoes in an integrated experiment in which analysis of ERTS-I MSS images has provided useful tectonic lineament information.

2. ERTS-I MULTISPECTRAL SCANNER IMAGE ANALYSIS

Large-scale tectonic lineaments of the Cascade Range have been identified on MSS images covering the following volcanic areas (figure 1): Mt. Baker, Mt. St. Helens, Mt. Rainier, Mt. Hood, Mt. Adams, Mt. Shasta, and Lassen Volcanic National Park (figure 2). The MSS image coverage of the Lassen volcanic area is particularly interesting and merits special attention.



Contour Interval 100 feet

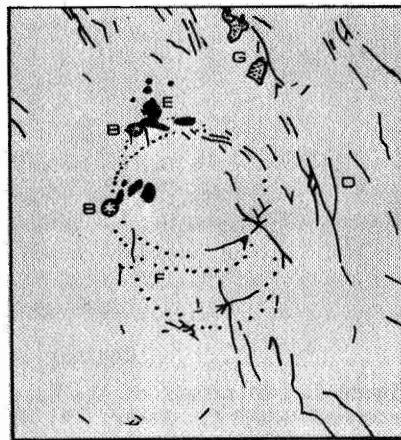
Figure 1: Volcanoes of the Cascade Range where thermal anomalies have been recorded. (A) Mt. Baker, (B) Mt. Rainier, (C) Mt. St. Helens, (D) Crater Lake (hydrologic anomalies), and (E) Lassen Volcanic National Park, (F) Mt. Adams, (G) Mt. Hood, and (H) Mt. Shasta. Thermistor arrays transmitting surface temperatures via DCP's and ERTS-1 satellite are sited at (A), (C), and (E) (two sets). Mt. Baker, Mt. St. Helens and Lassen have been active within the last two centuries.



Figure 2. Index map of the Lassen Volcanic National Park area. Scale: 1:1,000,000. Contour interval 300 feet. Area in box shown in figures 3A and B.



A



B

Figure 3A and B. Portion of ERTS-I, MSS image E-1075-18164, band 6, October 6, 1972: (A) Lassen Peak, (B) Brokeoff caldera, Battle Creek Meadows caldera, (C) Butt Mountain volcanic center, (D) mapped faults (solid lines), (E) dacite domes, (F) inferred lineaments (speculative), and (G) recent basalt flows. Fault and dome locations from Lydon et al. (1960).

Curvilinear features, several of which coincide with known fault lines in the southeastern part of the Lassen area are identifiable. Frames E-1075-18164, October 6, 1972, and E-1094-18224, October 25, 1972, in particular provide good stereopair coverage of the area. The synoptic effect of the images suggests a large circular feature, about 20 kilometers in diameter, centered on the North Branch, North Fork of the Feather River. Additional concentric features trend toward the south. In figures 3B and 4, previously mapped faults and other geologic features are shown with solid and dashed lines. Previously mapped fault zones, but which seem to be part of an unmapped larger pattern, extend along the Warner Valley from Lake Almanor northwest and then west toward the Brokeoff caldera of late Pliocene or Pleistocene age. Dacite domes, including Lassen Peak, are located along the northwest segment. A stratovolcano of Pliocene or Pleistocene age and related dacite domes are located along the western segment of the circular feature at Battle Creek Meadows (MacDonald and Gay, 1966). The concentric curvilinearments, shown as a dotted line, along the southern segment of the large circular feature, may encompass a large eruptive center of Miocene age near Butt Mountain. Lydon (1961) has proposed a source for volcanic tuffaceous sediments of the Tuscan Formation, of Pliocene age, in this same area near Butt Mountain.

Whether this circular pattern that appears on the ERTS-I images thus represents a large volcanotectonic collapse structure which developed in stages from Miocene time through the present is not yet clear. It is notable, however, that there appears to be structural control of the location of the Lassen dacite domes and specific structural control of the points of thermal emission along the Warner Valley faults.

3. AERIAL INFRARED SURVEYS AND THERMAL ANOMALIES

Night aerial infrared images (spectral bands 4.5-5.5 μ m and 8-14 μ m) were acquired over the Cascade Range volcanoes in 1972 expressly for this project (SR 251) by NASA's Manned Spacecraft Center's aircraft program, utilizing the RS-14 scanner operating in the NP3A earth resources aircraft, and by a U.S. Forest Service fire-detection aircraft equipped with a similar infrared scanner, operating under a cooperative agreement with the U.S. Geological Survey.

The results of the aircraft missions included plots of the major surficial thermal anomalies of the volcanoes listed below, showing the relationship of the anomalies to topography and geologic structure. Thermistor arrays transmitting temperatures of several anomalous areas via the ERTS-I Data Communications System, discussed in the next section, and related field reconnaissance investigations with a portable fixed-field PRT-10 infrared radiometer and bimetallic thermometer probes have provided temperature calibration or reference points for the infrared images.

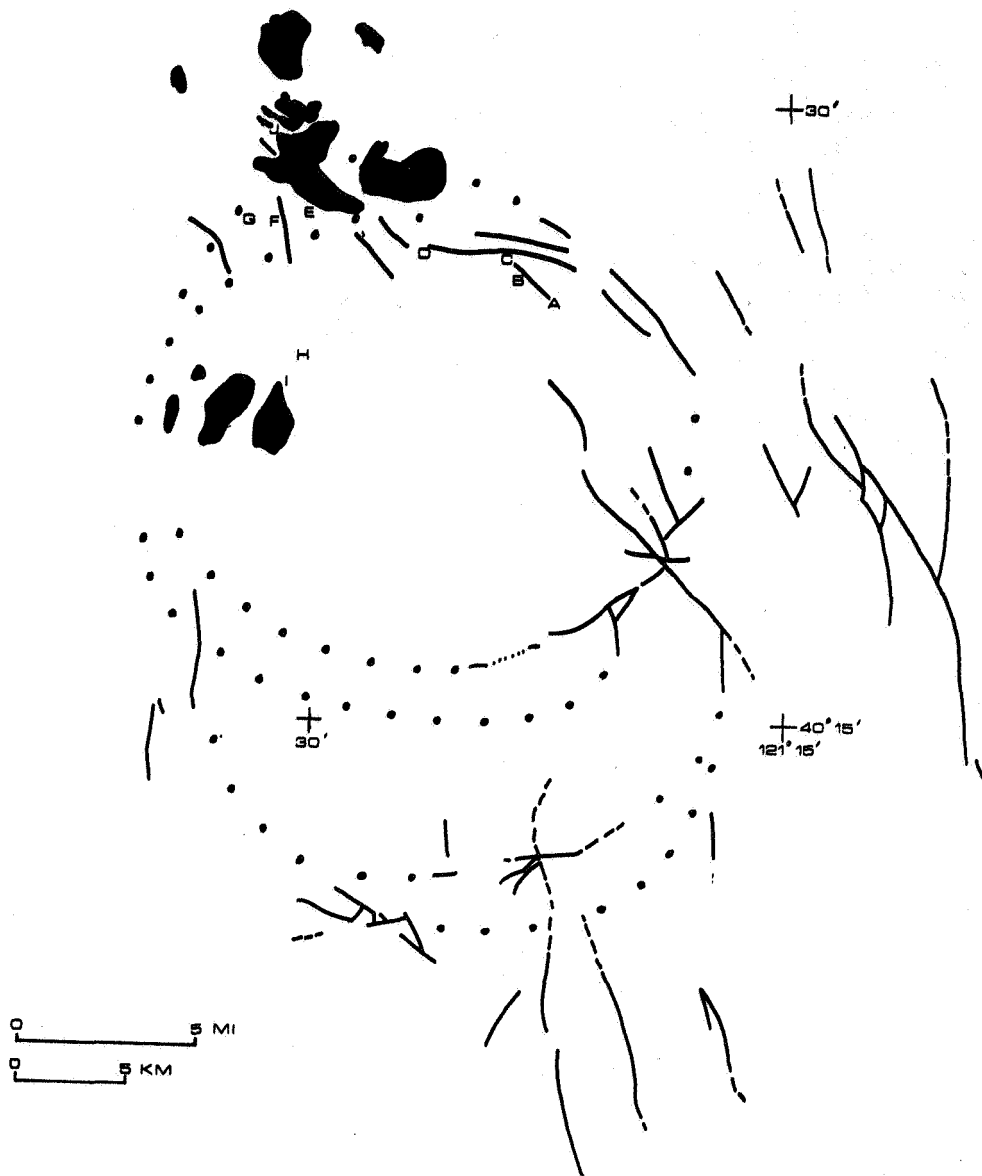


Figure 4. Structural control of geothermal manifestations and thermographic infrared anomalies in the Lassen Volcanic area, in relation to lineaments appearing in ERTS-1, MSS image E-1075-18164. Solid lines are mapped faults; dotted lines are inferred lineaments. Mapped faults and dome locations correspond to those shown by Lydon et al. (1961). Location of geothermal manifestations and infrared anomalies are shown by letters: (A) Terminal Geyser, (B) Boiling Springs Lake, (C) Drakes Springs, (D) Devils Kitchen, (E) Bumpass Hell, (F) Little Hot Springs, (G) Sulphur Works, (H) Growler Hot Springs, (I) Morgan Hot Springs, (J) Aligned NW-trending, infrared anomalies associated with Lassen Cone. Scale: 1,250,000. Thermistor arrays monitoring temperature changes are located at (B), (D), and (E). ERTS-1 satellite transmission from DCP's from (D) and (E).

Lassen Area. The major surface thermal manifestations of the Lassen volcanic area, as recorded on the aerial infrared images (figure 4, areas A-D; figure 5; figure 6), are aligned along faults depicted on the ERTS-I MSS images described above, particularly the Warner Valley fault system. One of the larger thermal manifestations here, Boiling Springs Lake, was radiating early in the afternoon of October 2, 1972 (prior to installation of a thermistor array) 1.8×10^2 watt m^2 from its surface, equivalent to an outward radiative flux of $4300 \mu\text{cal cm}^{-2} \text{sec}^{-1}$ (1.813×10^{-2} joules $\text{cm}^{-2} \text{sec}^{-1}$), or for the entire lake surface, a mean flux of $.713 \times 10^6$ cal sec^{-1} (2.985×10^6 joules sec^{-1}) ± 3.47 percent (standard deviation based on 16 scattered radiometric temperature readings on the lake surface, from inflow area to outlet, by PRT-10 radiometer). On Lassen Peak, the positions of smaller thermal anomalies are apparently controlled by the contact margins of historical or Holocene silicic or intermediate extrusive plugs and thus may mark a line of structural weakness along the upper reaches of Manzanita Creek Valley.

Mt. Shasta. Two anomalies were recorded in 1972 in a depression about 200 feet below the summit. No change is apparent since a previous aerial survey in 1966 (Moxham, 1970). The southern anomaly corresponds to thermal springs ranging from 72° - 84°C ; the northern anomaly may be similar.

Mt. Hood. Several anomalies which delineate warm ground and steam vent areas around Crater Rock, the Devils Kitchen, and Steel Cliff about 700 feet below the summit, were recorded in 1972.

Mt. St. Helens. Two barely perceptible thermal anomalies on a northeast trend were recorded in 1971 and 1972. The first anomaly corresponds to warm ground having a radiometric surface temperature of 36°C , 700 feet downslope from and southwest of the summit crater, approximately equivalent to a heat flow of $700 \mu\text{cal cm}^{-2} \text{sec}^{-1}$ (2.93 joules $\text{cm}^{-2} \text{sec}^{-1}$) on July 17, 1972. The epicenters of well-recorded earthquakes during the summer of 1970 also form a roughly linear pattern trending northeast from the summit of Mt. St. Helens (Unger and Mills, 1973, p. 1065-1066, figure 2).

Mt. Rainier. Thermal infrared images acquired in 1971 and 1972 reveal a distribution of anomalies similar to those recorded in 1964 (Moxham et al., 1965) and 1966 (Moxham, 1970). In April 1972, a pinpoint bright anomaly north of the main crater was recorded clearly for the first time since 1964.

Mt. Baker. The inside rim of the summit crater (100 feet below the summit) is lined with thermal anomalies, recorded in 1971 and 1972, and corresponding to warm ground and fumaroles emitting vapors through melt holes in the crater firn field. Representative temperatures for July 1972, are 60°C for the warm ground surface and 90°C for the

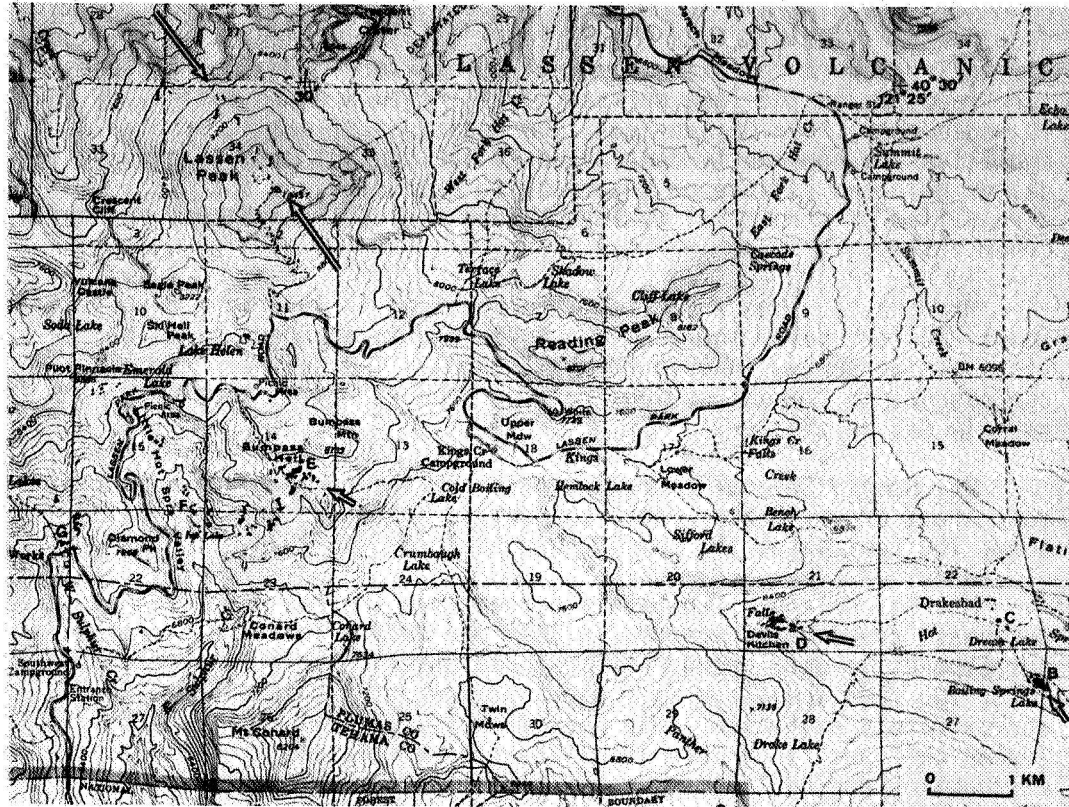
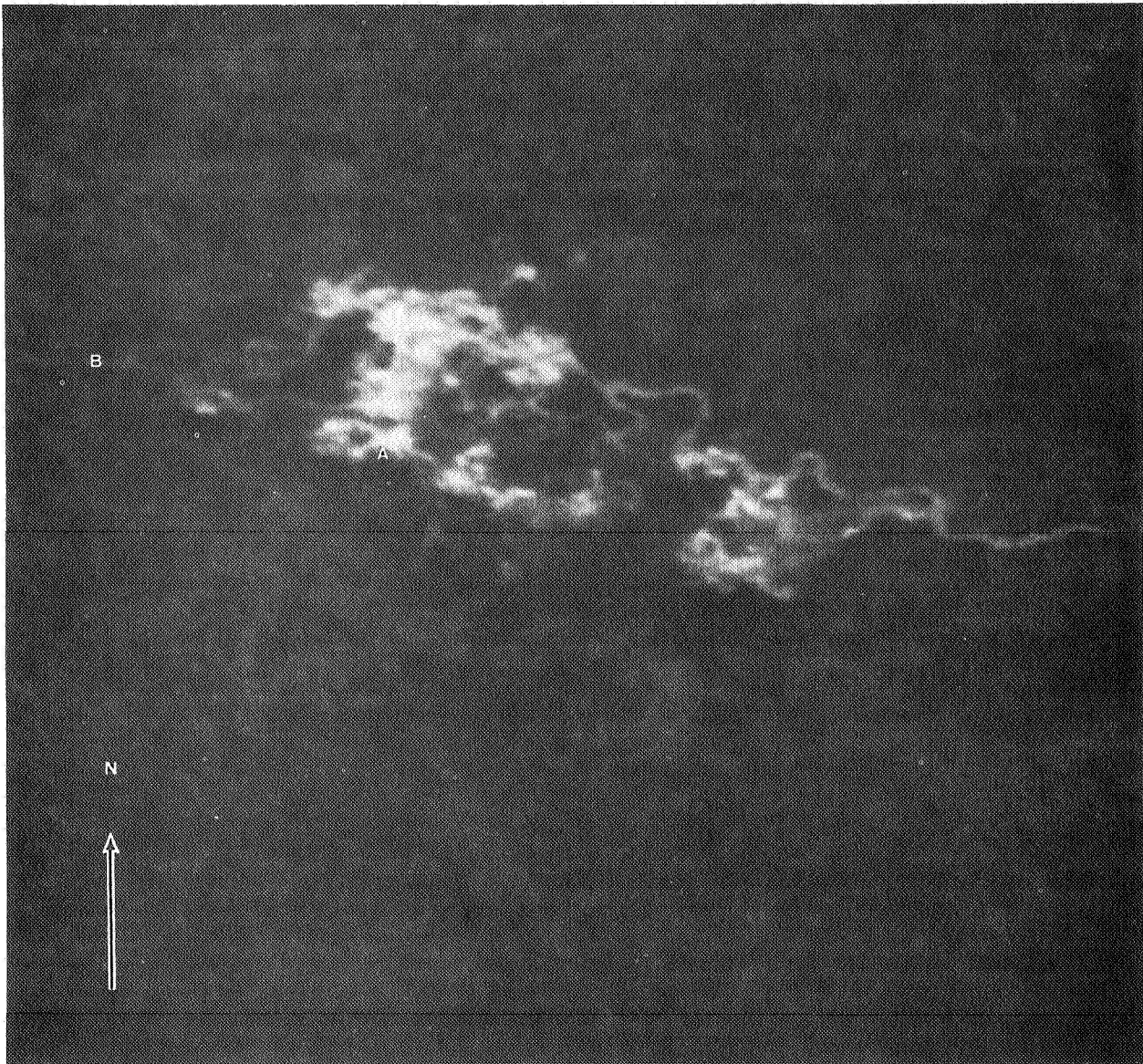


Figure 5. Thermographic infrared anomalies of April 20, 1972, 2041-2147 PDT, are as follows: (B) Boiling Springs Lake, (C) Drakes Springs, (D) Devils Kitchen, (E) Bumpass Hell, (F) Little Hot Springs Valley, (G) Sulphur Works, (J) infrared anomalies associated with the Lassen cone. Locations correspond to those in figure 4. Base from U.S. Geological Survey, Lassen Volcanic National Park and vicinity, 1957.



0 100 M

Figure 6. Aerial thermal infrared image of Devils Kitchen. April 20, 1972, 2130 PDT, flight altitude - 10,000 feet, $\frac{V}{H} = \frac{160}{3000}$. Polarity: black = cold, white = warm. (A) DCP 6104 thermal monitoring site, (B) Hot Springs Creek. Scale approximately 1:5000.

steam. A smaller thermal anomaly near the head of Mazama Glacier represents a fumarole area similar to that of the summit crater.

4. DATA COMMUNICATION PLATFORMS AND THERMISTOR ARRAYS

Four DCP's and two Fischer-Porter paper-punch tape recorders, each receiving temperature data from eight-probe thermistor arrays have been placed in operation (by February 1973) in carefully selected volcanic sites as part of ERTS-I experiment SR 251. (An additional site near the summit of Mt. St. Helens will be instrumented when weather permits in 1973.) Each site was selected to coincide with a thermal anomaly of volcanogenic or geothermal type which has been recorded on aerial thermographic infrared images. The temperature data can thus provide radiometric calibration points for the thermal radiation levels represented on the images, as well as time-dependent data showing temperature, radiation, and anomalous heat flow variations during the course of the experiment.

The following sites have been instrumented: (1) Devils Kitchen thermal area, Lassen volcanic area, California -- DCP 6104, Oct. 1972; (2) Bumpass Hell thermal area, Lassen volcanic area, California -- DCP 6020, Oct. 1972; (3) Boiling Springs Lake, Lassen volcanic area California -- Fischer-Porter paper-punch tape recorder operated by storage batteries and a servomechanism, Oct. 1972; (4) Mt. Baker, Washington, north slope fumaroles -- DCP 6251, Feb. 1973; (5) Surtsey Volcano, Iceland, thermal anomalies of tephra rim -- DCP 6056, Fischer-Porter system as above, Nov. 1972. A description of the Surtsey installation can serve as an example of a typical thermistor array-DCP site similar to those listed above.

Surtsey Thermal Instrumentation. On November 14, 1972, temperature measuring instrumentation including DCP set 6056 was installed on Surtsey volcanic island about 30 kilometers off the south coast of Iceland, and southwest of Heimaey. Eight temperatures are transmitted twice daily over the ERTS-I Data Collection System (DCS) and are recorded on paper tape every 32 hours.

The eight variables and their ranges are: air temperature (-25° to 25°C); nongeothermal ground surface (-25° to 25°C); geothermal ground surface (-25° to 25°C); and five one-meter geothermal probes (0° to 100°C). Linear thermistor networks encapsulated in stainless steel fixtures are the basic transducers. One-meter stainless steel rods were used for the geothermal depth probes, stainless steel prisms 2.5x2.5x12 cm, were used for the ground surface sensing, and a stainless tube, 1x8 cm, sheltered from the wind and sun was used as the air temperature thermistor mount. Each probe has a mating signal conditioner which, when power is applied, converts a full scale probe temperature change to a full scale range of 0 to 5.0 volts.

The ERTS DCP transmits data from eight analog channels every 90 seconds. During each transmission and 40 milliseconds (ms) prior to each transmission, the preamplifiers are turned on by command from the DCP. Total "on" time for the system is about 80 ms per transmission period. This low duty cycle allows a five to eight month battery life with about 16 kg of alkaline batteries. Transmissions were regularly received twice daily until December 25, 1972 when heavy winds may have blown over the antenna and interrupted data transmission. This station represents the greatest range over which the ERTS-DCS successfully communicated at the time of installation. Three steps were taken to ensure maximum possibility for transmission to the satellite: (1) maximum system voltage of 27 volts was used to give maximum rf output power (2) maximum transmission repetition rate of 90 seconds was used, and (3) antenna clearance to the southwest down to a 10 degree angle was taken into account during site selection.

A backup 16-channel paper tape recording system is operated in parallel with the DCP transmitter. Once every 32 hours the eight temperature parameters are recorded. A 32-hour cycle gives three different daily recording times spaced 8 hours apart which recur on a 3-day cycle. On command from the crystal controlled timer the preamplifiers are turned on and the parameters sequentially punched on the paper tape. After the last parameter, which is a reference voltage level used for a system check, the recording system and preamplifiers are shut off. Standby power consumption is about two milliwatts ($70 \mu\text{A} @ \pm 13.5 \text{V}$).

The successful installation and high quality message transmission (levels 6 and 7) over the ERTS-DCS demonstrates that data of this type may be reliably gathered with a thermistor array system of this nature in difficult environments and in very remote locations over a straight-line distance from Goddard Space Flight Center of 4800 kilometers.

5. SUMMARY

ERTS-I multispectral scanner images have been proved to be useful for tectonic lineament analysis, and in the Lassen area, show that the distribution of volcanogenic thermal anomalies as recorded on aerial thermographic infrared images are fault controlled in the Warner Valley. Time-dependent changes in temperature, radiation and anomalous heat flow from these thermal manifestations are being transmitted by the ERTS-I Data Communication Systems and are being recorded and analyzed by a U.S. Geological Survey IBM 360/65 computer program. Results are expected to give estimated variations in dormant or repose period anomalous thermal energy yield at the surface in the Lassen volcanic area. Similar data are expected from several other thermally instrumented sites.

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