Remote Infrared Detection of Uranium Ore Bodies

By
Robert J. Sopka

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado State University

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ABSTRACT

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In May, 1968 a preliminary survey was conducted over Martin Mesa in western Colorado to determine the feasibility of using infrared remote sensing techniques to locate subsurface radioactive ore deposits. The results of this study indicated a possibility that surface thermal anomalies induced by radiogenic heating were of detectable magnitude. Upon further investigation of the heat producing mechanism and execution of a more complete field program, however, there appears to be no question that any induced temperature differences at the surface are below the level of detection capability of commercially available infrared sensors.

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TABLE OF CONTENTS

LIST OF FIGURES

Chapter I

INTRODUCTION

The growing necessity for environmental management capability is demanding new and more comprehensive methods of data accumulation. To have a meaningful earth resources monitoring program, information must be available concerning large geographic areas with a minimum time differential. The techniques of remote sensing are the most potent tools available to accomodate this need.

Remote sensing is defined as the study of an object without intimate contact with that body. It incorporates areas such as seismic, magnetic, acoustical, and electromagnetic measurements. Each of these methods is being applied to various problems in environmental research but probably the most concerted effort at present is in the development of electromagnetic sensor systems.

Every body of matter has an array of radiation characteristics associated with it which is dependent on the physical and chemical state of the body. The size, texture, color, composition, and other qualities determine the absorbtivity, emissivity, transmissivity, and reflectivity of a body at a particular spectral wavelength. Therefore, by gathering information about the radiation characteristics of a particular body and fitting it in with known phenomena, it is possible to arrive at a signature method of identification.

The extent of the electromagnetic spectrum and the contributing properties of the body under study provide enough variables to make identification of certain physical qualities possible. This method of signature identification requires an extensive cataloging of known phenomena which, in most applications, is yet to be achieved. By perfecting the technology and applications of remote sensing, large quantities of information regarding the earth could be available from aircraft and orbiting satellites, thereby permitting rapid accumulation of data over large areas.

The present level of understanding and of instrumentation development in infrared technology makes it of primary importance to many investigations. From Wein's law it may be shown that the maximum thermal radiation from a surface at a temperature in the range of those found on the earth would be in the infrared wavelengths four to forty microns (Sellers, 1965). Therefore, using blackbody approximations it becomes possible to calculate the absolute temperature of the emitting surface from infrared measurements.

Of additional significance in the application of infrared sensing systems is the relatively high transmissivity of the atmosphere to the infrared wavelengths, especially in the 8-12 micron interval. This is commonly known as the "atmospheric window."

Surface infrared thermal mapping from aircraft and satellites is currently being put to use in a number of meteorological studies, and other applications are being developed for earth resources mapping projects. The ability of infrared sensors to scan with rapidity extensive areas on the earth's surface provides a heretofore unrealized opportunity for variation of observational perspective. Depending on the technique involved, information may be gathered over a much larger geometric and smaller time scale than previously possible. In meteorology in particular, the use of satellites allows a global viewpoint of weather systems from an orbit with a period on the order of hours. Little (1968) gives a brief summary of the status and proposed applications of the weather satellite system.

Similar infrared techniques are now being developed for astronomy, oceanography, agriculture, and pollution studies. Ewing (1965) noted a number of oceanographic applications and pointed out their particular value in collecting data where conventional observation facilities would be highly impractical.

Thermal mapping of inland water bodies makes it possible to locate the source and extent of pollution. In agriculture, remote sensors are being used for crop and disease mapping.

By looking outward through the "atmospheric window," astronomers have gathered data on the apparent surface temperatures of neighboring planets. Murray et. al. (1963) and Wildey (1965) have been able to map the thermal features of the cross sectional areas of Venus and Jupiter respectively.

Perhaps the major potential use of infrared sensing of the earth is in the field of geology. There are a number of geologic features which readily lend themselves to thermal detection. These are the large heat producinq mechanisms such as subsurface coal fires, volcanic activity, and geyser and hot springs areas. Slavecki (1965), among others, has used thermal mapping techniques to detect and locate subsurface coal fires, while Miller (1966) did a similar study over the hot springs area of Yellowstone National Park. Volcanic activity in Hawaii has been studied by Fischer et. al. (1964).

The common property that makes these phenomena easily detectable is their large anomalous heat production which warms the local surface temperature to a significant degree so as to be detectable with an infrared sensor. There exists, however, a number of other heat producing mechanisms which are not quite so large as those discussed above but in certain instances may be detectable. Into this category fall naturally occuring chemical reactions and nuclear decay processes.

The state of the art is so new that in virtually all of the previously mentioned areas of study only the gross features have been well documented and substantiated. There exists a lack of solid scientific evidence at present to show that most of the smaller scale features would lend themselves to infrared detection. In geology in particular, detection of these smaller scale features could lead to many new methods of prospecting and mapping of ore deposits.

On May 11 and 12, 1968 a preliminary exploratory survey was conducted with an infrared radiometer to map the surface thermal features of Martin Mesa in western Colorado. Located in the main uranium mining district of the state, Martin Mesa has produced a substantial ore yield and is known to be an area with rich deposits.

In this study, a Barnes IT-3 thermal radiometer mounted in a light aircraft was flown on overlapping paths across the mesa to construct a two dimensional temperature map of the ground surface. When the data was reduced and compiled, there appeared a number of locations with unaccountably anomalous heat flow. These particular locations were outlined on a United States Geological Survey (U.S.G.S.) topographical map of the area and published by the Martin Marietta Corporation of Denver, Colorado (Muhm et. al., 1969).

During the course of a subsequent dust drilling program, signs of uranium ore deposits were found under some of the areas on the mesa noted to be anomalously warm. Since the drilling program is unfinished, however, complete verification is not possible at this time. The limited success of this preliminary survey indicated that further study of the problem was certainly warranted.

It is, therefore, the purpose of this paper to test the hypothesis that uranium ore can be detected with an infrared sensor. Evidence to define the limits of truth of the hypothesis will be presented.

The following chapter will present respectively a) a theoretical treatment of the problem and b) the results of a field study of infrared sensing over a known uranium ore deposit.

Chapter II

THEORETICAL MODEL

As a first approach to the problem of detecting the thermal features of uranium ore deposits, it appears reasonable to apply the theory of heat transfer and to consider the predictions obtained from the mathematical model. In this section a simplified model will be developed using values substantiated by various investigators to try, in theory, to assign limits to the magnitude of the expected surface temperature anomalies.

The mechanism for heat production here is the nuclear decay of U^{238} through its thirteen daughter elements to a final stable state of Pb^{206}. In this process a total of eight α particles are emitted at various stages of decay. According to Birch (1954), the mass to energy conversion in the reaction:

$$U^{238} \longrightarrow Pb^{206} + 8He^{4}$$

affords a method of calculating the amount of heat produced per unit time per unit volume of U^{238}.

The penetration distances of the α and β particles are small enough to assume that their kinetic energy is converted to heat energy at the source. A correction must be made, however, for the energy carried away by the neutrino production.

Stern (1949) shows the mass difference in the total decay process to be 52.2Mev, which, when corrected for neutrino loss, yields a value of 3.07 joules/year/gm U^{238} (McDonald, 1961) or .73 cal/gm U^{238}/year of heat production. Birch (1954) describes the details of this calculation and also shows heat generation values for Th^{232} and U^{235} decay processes.

These other two elements often occur in natural uranium ore deposits in a fixed ratio to U^{238} depending on the type of ore. However, as a normal occurance in sedimentary rock the ratios are so small as to be beyond detection. This exceedingly small ratio is particularly common for ore bodies found in the regions of western Colorado.

By considering anomalies rather than absolute values of temperature it is possible to assume a steady state condition. To justify this important simplification, a comparison can be made of the surface temperature of an area over an ore deposit to its surroundings. Considering all of the heat fluxes across each of the two surface boundary layers, a determination can be made of the actual temperature of each. The distance required to move out of the region of influence of the ore deposit is relatively small (<1000 yards). Therefore, subtraction of the two temperatures and hence the summation of the contributing heat fluxes yields a temperature difference which depends only on the difference in net heat flux between the two areas. In other words, due to the close proximity of the two areas, the diurnal, seasonal, and geothermal contribution to the total heat flux through the ground surface over a deposit may be taken to be identical to the contribution in a neighboring region. Subtraction will cancel the effects of these contributions leaving the resultant ΔT to be a function of the radiogenic heat, which is not a function of time.

To complete the argument for neglecting time as a variable; investigation shows that the primary radioactive constituent of the ore, U^{238}, has a half life of 4.51×10^9 years, which according to MacDonald (1964), is on the order of the lifetime of the earth. Consequently, the disintegration rate may be assumed constant for the time intervals of interest here.

Since the mechanism and rate of heat generation is now known to a reasonable accuracy, it should be possible to realistically model this heat source at any given depth below the surface. Using the appropriate boundary conditions a solution to LaPlace's equation $\nabla^2 T = 0$ would yield a surface temperature map above the source (Carslaw and Jaeger, 1959). For this case, however, the same result may be demonstrated by selecting a more simplified model. By constaining the heat source (ore deposit) to lie in an insulated well, a number of assumptions are possible which will allow for a simple calculation of an overestimate of the surface temperature anomalies.

In reality, the surface is at a lower temperature potential than the interior of the earth which means that all of the heat flowing from a subsurface source will pass through the surface boundary. By using the insulated well constraint there will be no divergence of heat flow and thereby the depth of the deposit will be eliminated as a variable.

Since the temperature of the system is assumed to be in equilibrium, all of the heat flowing from the source must arrive at the surface boundary over the same area. The mechanism for the transport of this energy away from the surface will determine the temperature of the surface.

If U^{238} is assumed to appear in the ore as the mineral uraninite (UO_2) (Katz and Rabinowitch, 1951) at a given volume percentage and thickness of ore body, the heat production can be calculated by the equation.

$$\psi = (\%vol)(D)(\rho uo_2)(R)(H)$$

where

ψ = heat production of ore body (cal/cm^2 - sec)

%vol = volume percentage of UO_2 in ore

D = thickness of ore (cm)

ρuo_2 = density of UO_2 (10.9 gm/cm^3)

R = ratio of molecular weight [238 gms U^{238} / 270 gms UO_2]

Figure 1 shows the values of ψ plotted as a function of volume percentage for various values of D.

In the insulated well model, ψ is also the amount of heat energy arriving at the surface boundary. This heat energy can be assumed to be radiated away, since conductive energy loss, under these circumstances, would be approximately two orders of magnitude less than radiative energy transfer.

For anomalies of 1.0°K and 0.5°K as plotted in Figure 2 the energy loss can be calculated from the Stephan-Boltzman Law:

$$\Delta W = \varepsilon\sigma(T_s^4 - T_a^4)$$

where

ΔW = the radiative energy transfer difference between the region over an ore deposit and its surroundings

ε = emissivity [taken to be 0.90, (Buettner and Kern, 1965)]

σ = Stephen Boltzman constant 1.337×10^{-12} cal/cm^2-sec

T_s = temperature (°K) over the deposit

T_a = ambient surface temperature (°K)

In comparing Figures 1 and 2, the heat required for a 0.5°K anomaly at a T_a of 300°K would necessitate an ore deposit of 2.1% by volume UO_2 with a thickness of 75 meters or a 50 meter thick deposit of 3.2% UO_2. From these examples it is apparent that even with this overestimating model extreme values of thickness and/or concentration are necessary to provide a temperature anomaly of minimum size. Such deposits are high uncommon in nature. It is therefore concluded that the radioactive decay process itself does not generate enough heat to produce a distinguishable surface temperature anomaly.

The very limited experimental work to date on remote sensing of temperature anomalies over uranium ore deposits

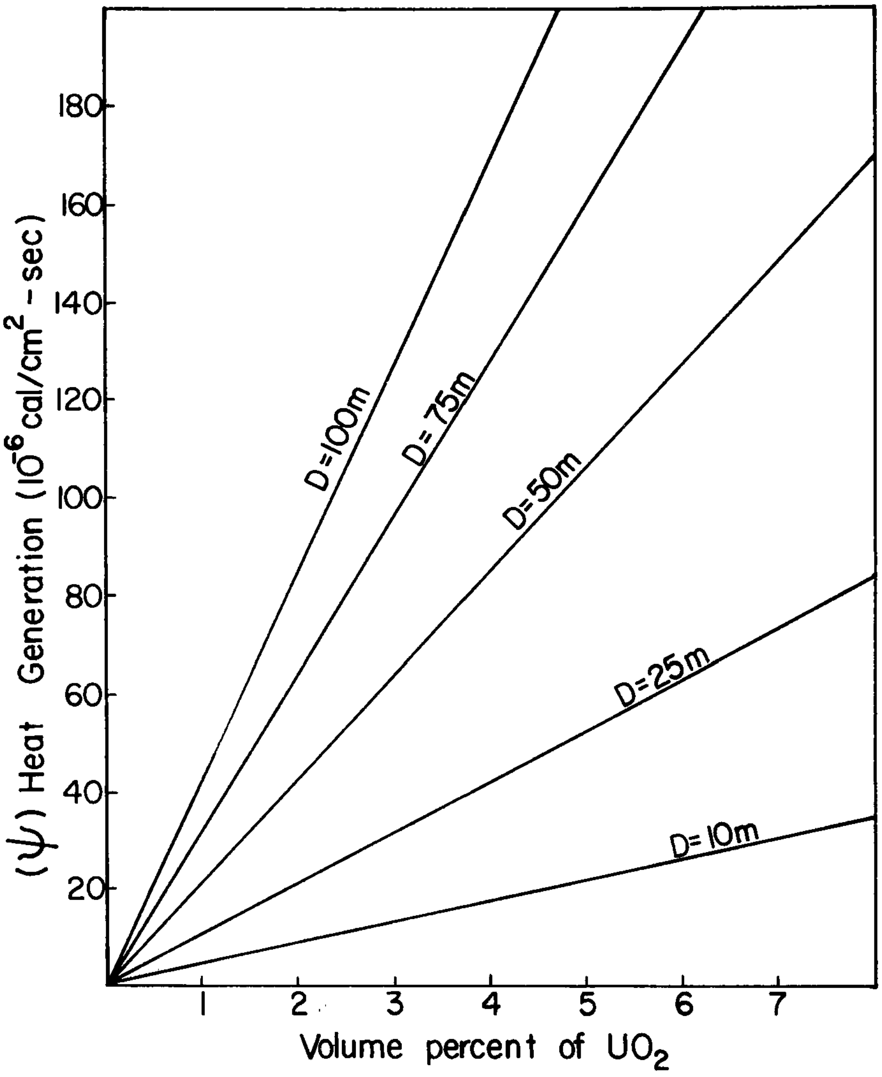

Figure 1. Amount of heat generated (ψ) by a uranium ore body as a function of volume percentage of UO_2 (%vol) and thickness (D).

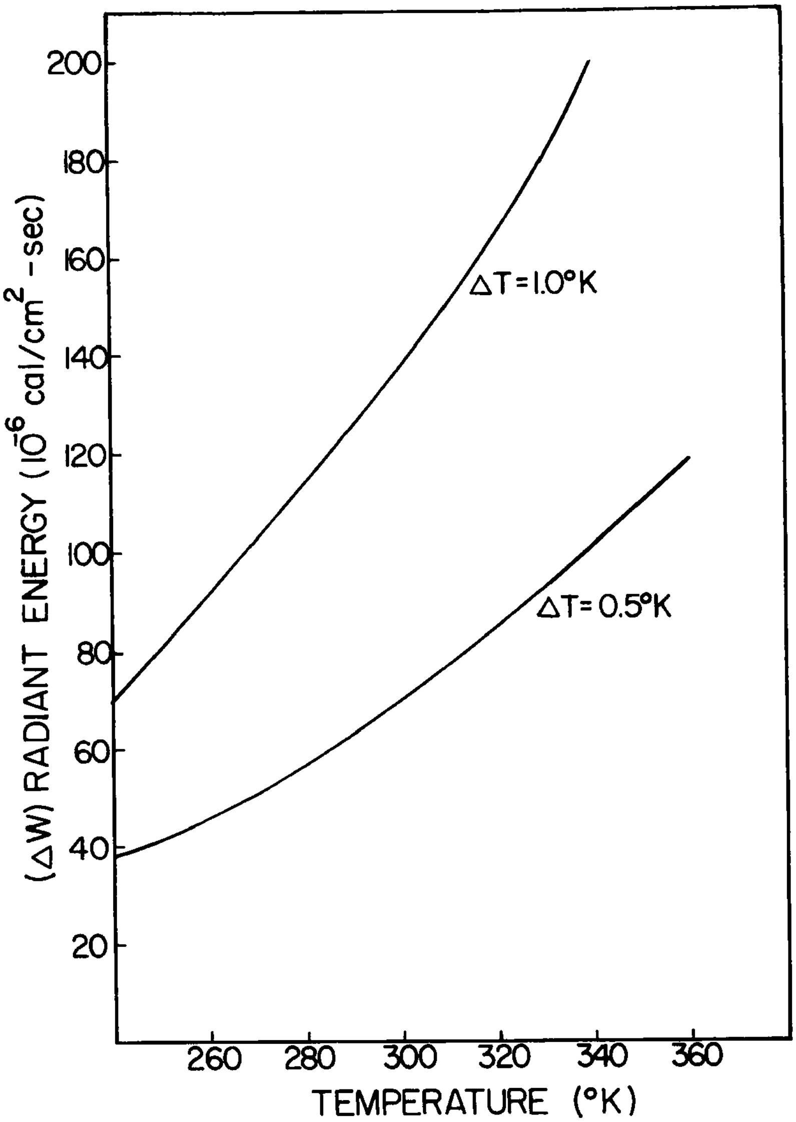

Figure 2. Difference in radiant energy emission (ΔW) for a surface temperature difference (ΔT) where the surface has an ambient temperature (T).

does, however, seem to indicate the possibility that the anomalies are larger than the above model indicates. Perhaps there exists some as yet undiscovered corrollary effect to account for this or perhaps the heat generation processes are not yet fully understood. Because of the apparent discrepancies between theroetical and preliminary experimental results a field study was undertaken to attempt to determine whether there is, in fact, any substantive evidence for the occurance of this phenomenon.

Chapter III

EXPERIMENTAL PROGRAM

Although the results of the heat transfer model indicated no strong positive temperature anomaly, there could exist factors relating to the temperature field associated with natural uranium deposits which were not taken into account. In order to evaluate the technique used in the Martin Mesa study, a more complete and systematic field program was undertaken.

The region selected for the field study was the Shirley Basin in Wyoming - a highly productive uranium ore producing area. At the present time there are extensive open pit mining operations in the Shirley Basin and a number of studies have been conducted by geologists to locate the ore fronts and ore bearing regions (Harshman, 1968). The vegatation is rather sparse and very homogeneous over large areas, thereby minimizing surface emissivity differences - an important consideration in the analysis of radiometer measurements. All of these factors favored the Shirley Basin as an ideal location for determining whether known uranium deposits could produce detectable surface heat anomalies.

In order to minimize ambient thermal radiation and surface "noise," the time chosen for the study was the late spring, when the snow cover had disappeared. All measurements were made at the first light of dawn to eliminate diurnal heating effects. The flights were made before sunrise on the mornings of May 8, 9, 10, and 13, 1969.

A Barnes precision radiation thermometer, model PRT-5, was mounted in a Cessna 180 aircraft with the viewing head pointing vertically downward through the cabin floor. The radiometer was connected to a strip chart recorder with a power supply in series to permit maximum scale variation on the recorder. In order to correlate the strip chart data display with the actual ground location, the flight paths were chosen to include natural landmarks with marked temperature differences. such as lakes. roads, and rivers. Two flight paths were selected for a degree of repeatability in the experiment, one running east-west and the other running north-south. The east-west route (designated flight path #1) was particularly advantageous in that it covered only natural terrain and was perpendicular to four ore fronts. The north-south line (called flight path #2) ran roughly parallel along the main ore front but covered large areas where the pit mining operations had decidedly altered the natural surface conditions. Because of the possible data contamination by the mines, most emphasis was placed on the results of flight path #1.

Since the field of view of the radiometer is three degrees and its output signal is an integrated average value of the thermal emission in the area it "sees," it is imperative that this instantaneous viewing area be not larger than the size of the anomaly region sought. Harshman (1968) found that the size of the deposits along the ore front are about 10 to 20 feet in horizontal extent, therefore, the aircraft was flown at an altitude of approximately 500 feet above ground surface. Flying lower than 500 feet was not possible due to the need to keep the flight path landmarks in sight. Figure 3 is an overlay of the U.S.G.S. topographic map of the Shirley Basin showing the flight paths and the ore bearing regions.

It may be noted from Figure 3 that flight path #1 begins in the east at the Medicine Bow River, crosses the Moss Agate Reservoir and terminates in the west at an unnamed pond to be referred to as West Lake in this report. These three water bodies had significantly higher temperatures than the ground surface and therefore were most useful in fitting the strip chart data to actual ground locations.

Throughout the field program, the weather remained cloudless and precipitation was never a factor in changing the moisture content of the soil.

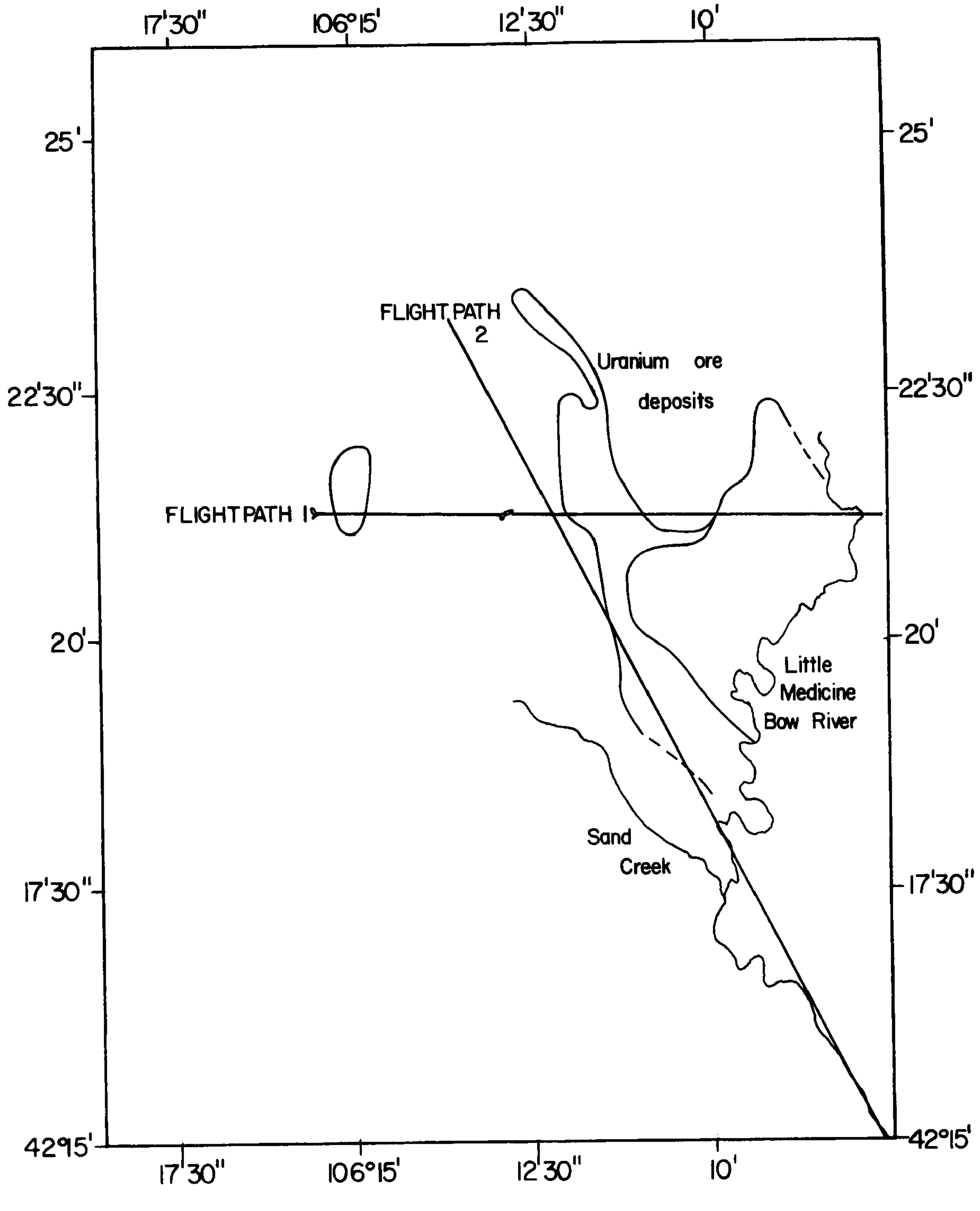

Figure 3. Overlay of the U.S.G.S. topographic map of the Shirley Basin, Wyoming depicting the location of the flight paths and the location of the uranium ore deposits.

Chapter IV

DATA ANALYSIS

During the course of the field study a total of seventeen complete overflights were made, ten for flight path #1 and seven for flight path #2.

In order to make meaningful comparison of the data records, it was necessary to convert them to a common time scale. By varying the recording time interval during the analog to digital reduction, it was possible to force a coincidence of the end points on the digitized records for each of the two flight paths. The time increments involved were small enough to impose little or no high frequency analog signal loss in the data.

During the course of the field study, the data was gathered over different voltage output and recording scales. Consequently it was necessary to reduce the raw data to a common temperature scale in order to perform a quantitative comparison analysis.

Upon completion of the field program, the PRT-5 radiometer calibration was checked against a standard black body cavity in the laboratory. The proceedure involved recording the radiometer voltage output for a number of controlled temperature values in the calibration system. Since the calibration curves showed a linear variation of voltage with temperature it was necessary to perform a rather simple linear transformation on the raw data to reduce it to a common temperature scale.

Each data case was subjected to a smoothing operation in order to remove incidental high frequency signals. The technique of "running means" was applied over an interval of two data points to either side of the point to be smoothed. This seemingly small interval was chosen to insure that no meaningful signal be removed or minimized and to eliminate only those frequencies definitely smaller than those sought.

Figures 4, 5, 6, 7, and 8 show the individual data cases for flight path #1 as they appear after the above operations were performed and after each case was reduced to a zero mean. Figure 9 shows the average of all cases. Since only temperature differences are of interest here, the zero mean representation permits an easy comparison of cases. In addition, effects of the daily variations of the average temperature over the entire region and possible day to day instrumentation inconsistencies are eliminated by reducing each case to a common mean.

As pointed out at the end of the previous chapter, three water bodies were included in flight path #1 and they appear as the largest peaks in the temperature profiles of Figures 4, 5, 6, 7, and 8. These profiles are plotted such that east is to the left in the figures.

It is necessary perhaps to emphasize that only temperature anomalies and not absolute values are of significance. As pointed out in Chapter II, the actual ambient temperature

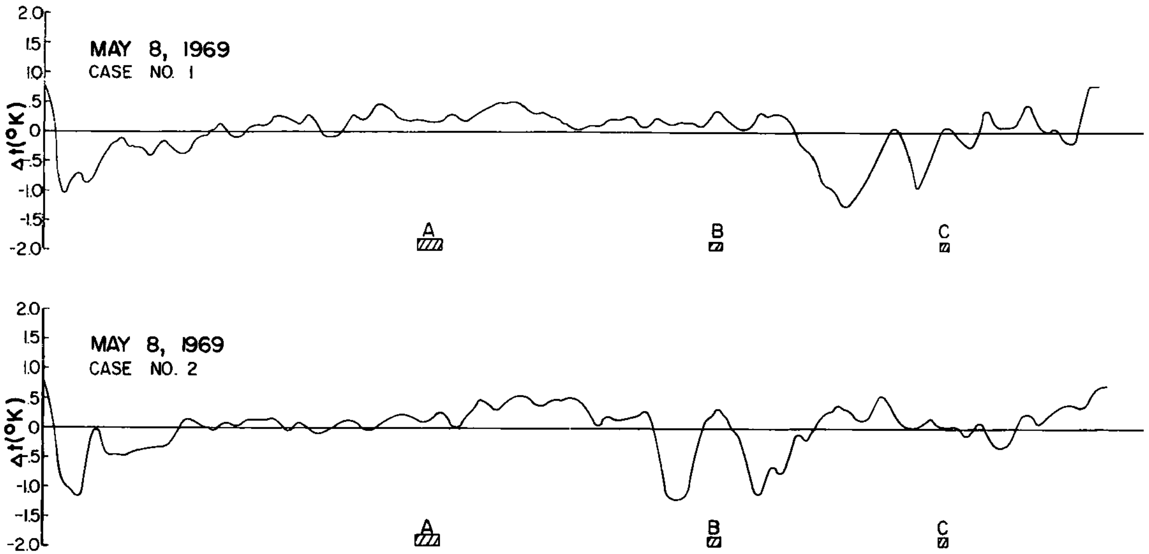

Figure 4. Reduced temperature profiles for flight path #1, cases 1 and 2. Δt is the temperature relative to a zero mean temperature (see text). Locations designated A, B, C, and D specify areas of uranium deposits.

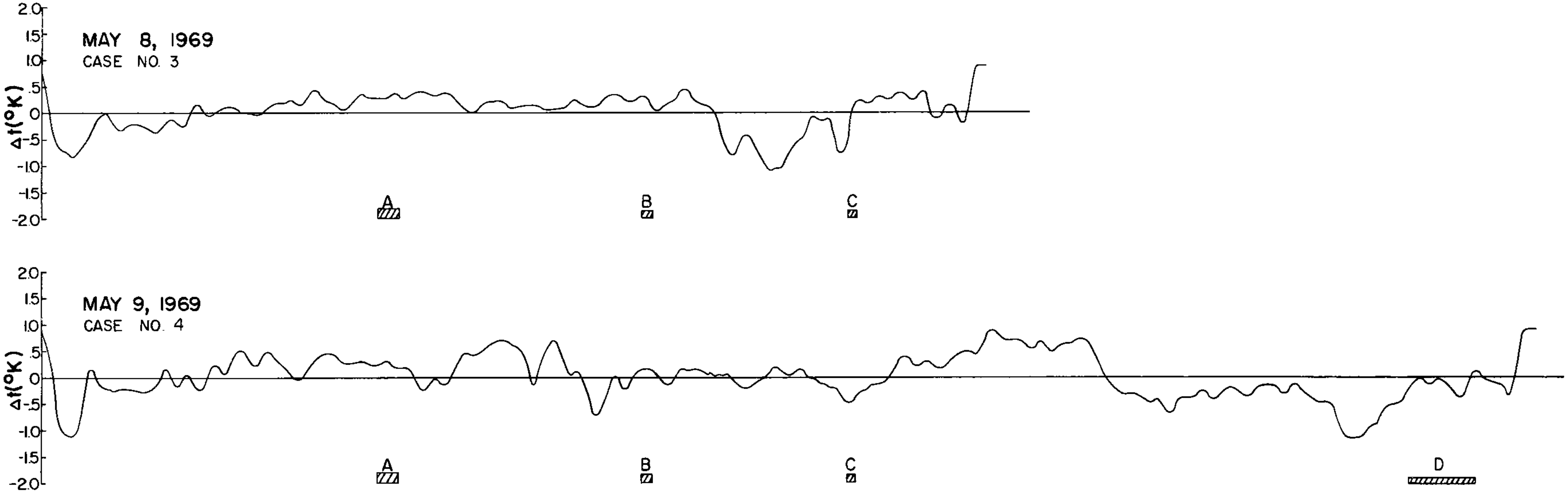

Figure 5. Reduced temperature profiles for flight path #1, cases 3 and 4. Δt is the temperature relative to a zero mean temperature (see text). Locations designated A, B, C, and D specify areas of uranium deposits.

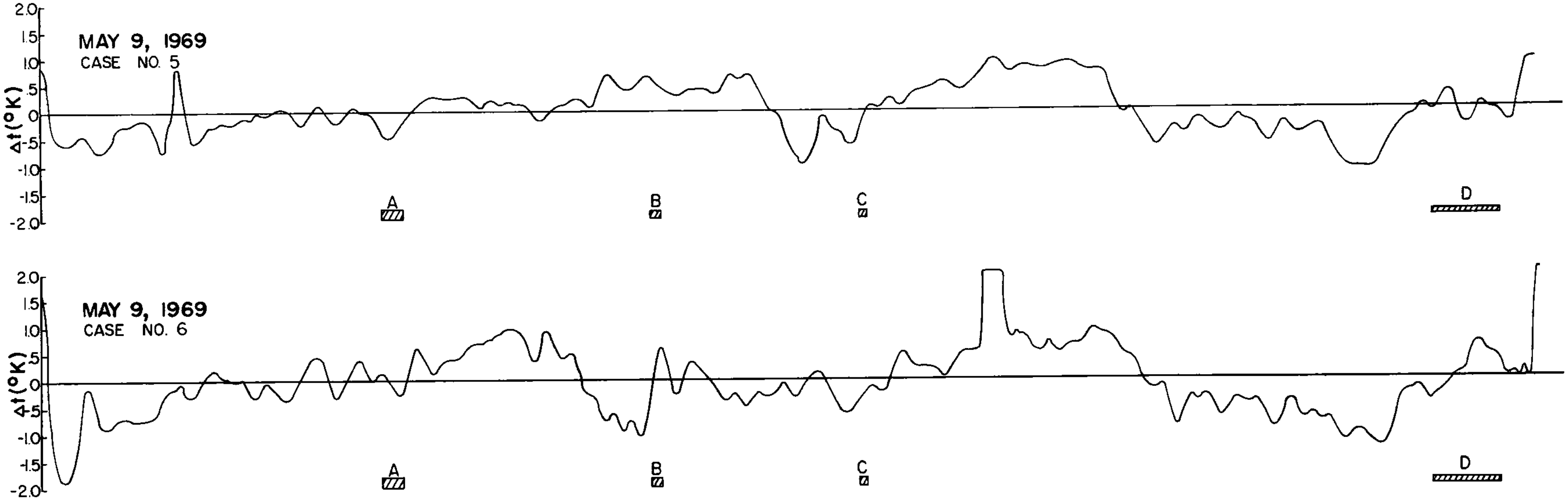

Figure 6. Reduced temperature profiles for flight path #1, cases 5 and 6. Δt is the temperature relative to a zero mean temperature (see text). Locations designated A, B, C, and D specify areas of uranium deposits.

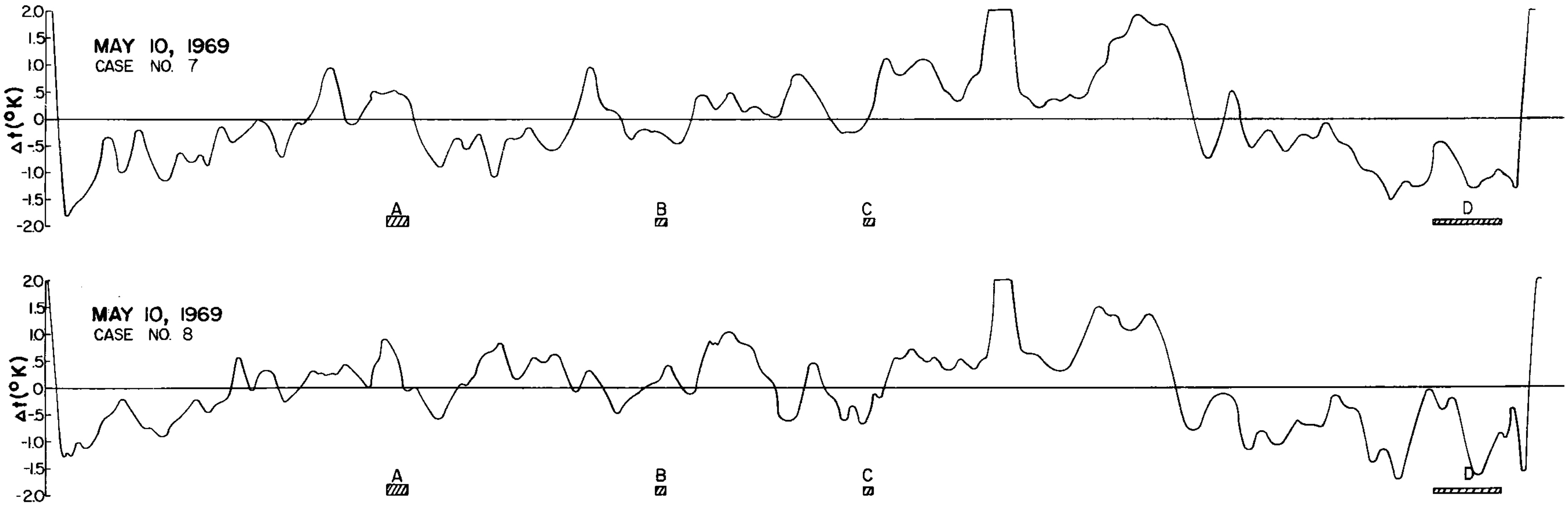

Figure 7. Reduced temperature profiles for flight path #1, cases 7 and 8. Δt is the temperature relative to a zero mean temperature (see text). Locations designated A, B, C, and D specify areas of uranium deposits.

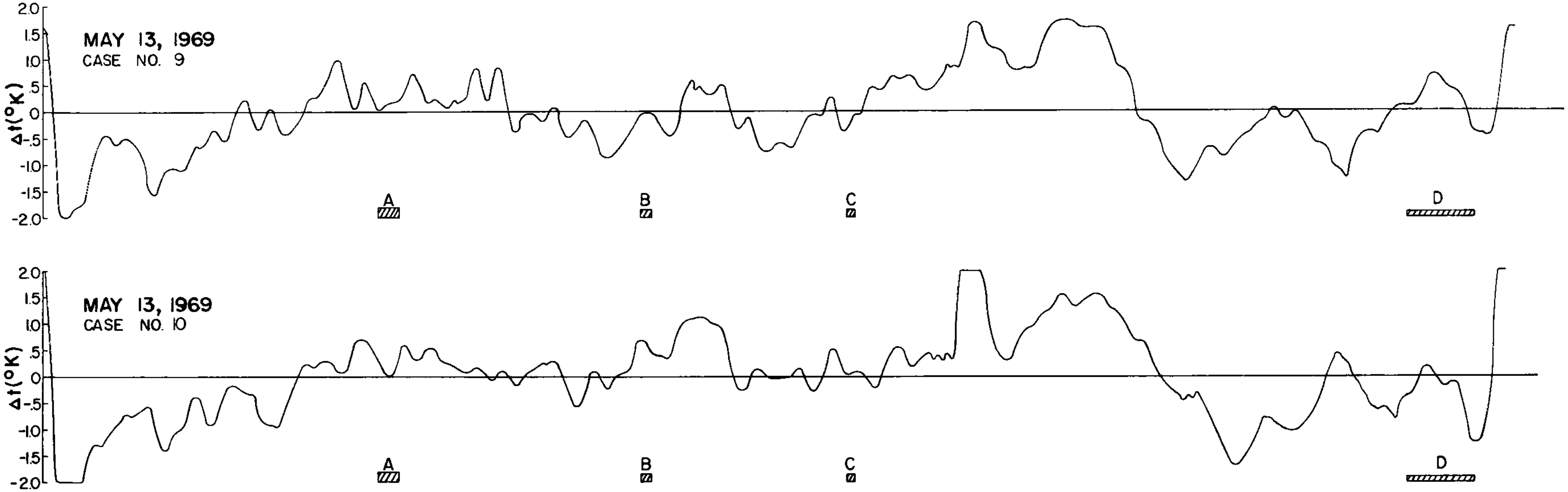

Figure 8. Reduced temperature profiles for flight path #1, cases 9 and 10. Δt is the temperature relative to a zero mean temperature (see text). Locations designated A, B, C, and D specify areas of uranium deposits.

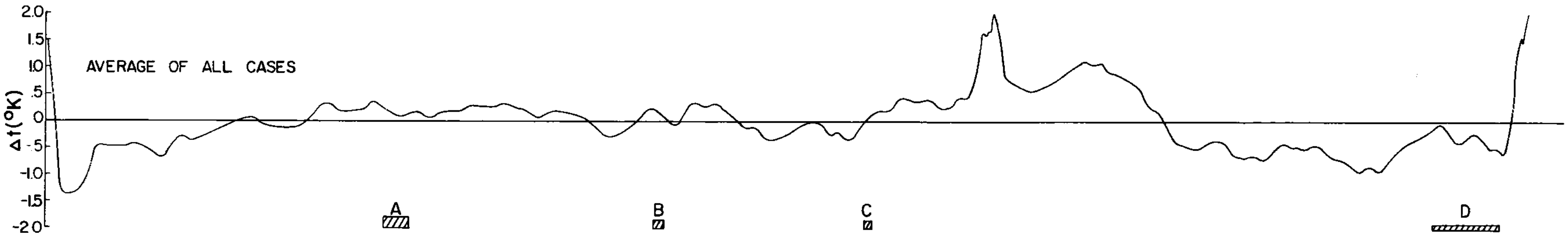

Figure 9. The average temperature profile for flight path #1 computed from all cases. Δt denotes the temperature deviation from the mean. Regions A, B, C, and D specify the locations of the uranium ore deposits.

of the ground surface is of little consequence since the surface temperature anomoly induced by radiogenetic heating is superimposed on the diurnal and seasonal temperatures. This type of investigation is possible only for conditions where the surface temperature falls between specific values. This temperature range is bounded on the lower end by the freezing point of water (273.6°K) and on the upper end by the temperature at which the surface "noise" overrides the anomaly (approximately 300°K). Inspection of Figure 2 bears this point out.

To quantitatively compare these data displays, analysis was directed at indicating the systematic part of the signal i.e. those thermal features that occur most often. The portion of the entire signal due to surface noise should be significantly more random than that due to heating anomalies related to specific phenomena. Over areas of uranium ore deposits the temperature traces should therefore, approach a greater degree of coincidence than in other regions. Under this premise it would appear that an analysis of variance performed on the temperature values over each particular location would differentiate between the areas of random signal and systematic signal. Recalling the results of Chapter II and from inspection of Figures 4, 5, 6, 7, and 8, however, it is apparent that the temperature profiles over the ore deposits are the same order of magnitude as the random noise.

The plot of the average of all cases (Figure 9) shows some areas where the temperature deviates markedly from the mean. Therefore, rather than simply analyze the distribution of the variances, it would further strengthen the argument to weight the variance for the regions where the temperatures differ from the mean, such that as the mean is approached a smaller variance will be tolerated. This is somewhat analogous to the coefficient of variation computation (Miller and Freund, 1965). Rather than divide the variance by the square of the mean of the sample, however, the second moment about the zero axis was used.

As previously indicated, this analysis scheme is heavily biased in favor of a systematic deviation of the temperature from the mean. By using this type of analysis procedure, however, it becomes apparent that there is not a sufficient degree of consistancy in the temperature profiles over the ore bearing regions.

The equation used in this technique was

$$\frac{s^2}{t^2} = 1 - \frac{\bar{t}^2}{\overline{t^2}}$$

where:

$$\bar{t}^2 = \left(\frac{1}{N} \Sigma\, t_i \right)^2$$

$$\overline{t^2} = \frac{1}{N} \Sigma\, t_i{}^2$$

and

s^2 = variance of the temperatures measured over a particular location.

t_i = values of the temperatures over that particular location.

It should be noted that this is merely the usual equation for the variance of a sample divided by the second moment about the zero axis (which in this case is the average temperature of the entire area covered by the flight path). The factor:

$$R = \overline{t}^2/\overline{t^2}$$

was calculated for each location and plotted in Figure 10.

The quantity R is an index of the weighted variance described above. Its maximum values appear where the spread of the points (S^2) is small and the distribution of those points about the zero ($\overline{t^2}$) axis is large.

In comparing Figure 10 to the plots of each horizontal temperature profile (Figures 4, 5, 6, 7, and 8) and the graph of the average profile (Figure 9) the most notable maxima occur in regions E, F, and G. These regions are the locations where the temperature most consistantly deviates farthest from the mean. Region E is immediately west of the Medicine Bow River, the eastern starting point for flight path #1 and shows a temperature consistantly far below the mean. Region F is immediately west of the Moss Agate Reservoir and covers the only area of significant topographic inconsistancy. Region G is the only location of these three that includes a known uranium deposit (Region D) but the temperature trend is well below the mean.

Inspection of the value of the index R over the other ore bearing regions (Regions A, B, and C) show no indications whatever that the signal is anything but random.

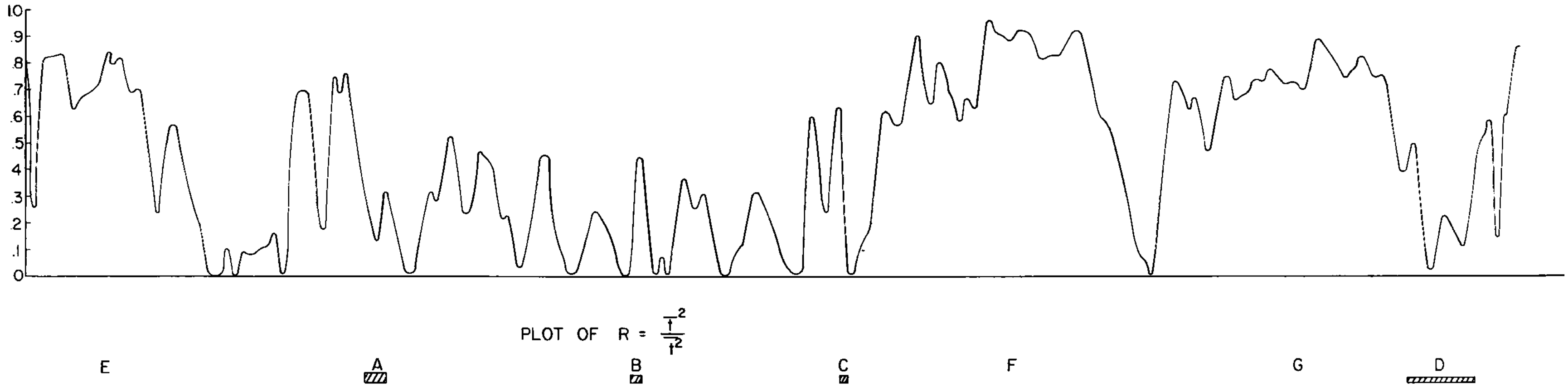

Figure 10. The plot of the analysis parameter R computed for all cases over flight path #1. Regions A, B, C, and D specify locations of the uranium ore deposits. E, F, and G designate features of the curve discussed in the text.

Chapter V

CONCLUSIONS

The results of the data analysis show three ore bearing regions to produce no definite detectable surface temperature difference, while the remaining region indicates the possibility of a slight positive deviation. Consequently, it must be concluded that uranium ore deposits do not lend themselves to surface thermal detection.

In explaining this negative result, the foremost contributing factor is the small signal to noise ratio. It is immediately apparent from the reduced data cases that any temperature rise over these deposits is buried in the random noise. This was further substantiated by an analysis technique which was biased in favor of any possible consistant temperature rise but still showed no positive result.

There seems to exist no possible way of further minimizing the surface noise contributions since the time of the flights was chosen to reduce these effects as much as possible and the area chosen for study was quite homogeneous in topography and surface vegatation.

Since it is possible that most of the random signal is due to differences in surface emissivities and microclimatological effects, perhaps a sensor system that "sees" a signal generated at a greater depth than the very slight infrared skin depth could prove useful. Such a technique is afforded by microwave sensors and was explored by Strangway and Holmer (1966) in a search for oxidizing ore bodies. The use of longer wavelengths fulfills the skin depth requirement but these frequencies are very strongly absorbed by water. Thus the soil moisture content and the level of the water table are two complicating factors which are not easily handled.

In conclusion, it is quite apparent that the presently available commercial infrared sensors do not afford an adequate method for detecting subterranean nonconducting ore deposits. Perhaps further investigation into the application of microwave sensors to this problem might prove fruitful in some instances where the soil is moisture free. In any event however, the pursuit of such a technique still remains a valid goal in an earth resources project. The economic benefit to be derived from optimum exploitation of mineral deposits could perhaps be the most important result of the future earth resources program.

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