RADIATIVE PROPERTIES OF ROCK TYPES IN THE HARQUAHALA PLAINS AREA, ARIZONA AND POSSIBLE METEOROLOGICAL IMPLICATIONS

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF HYDROLOGY

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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STATEMENT BY AUTHOR

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ACKNOWLEDGMENTS

The author wishes to thank first and foremost Mr. H. E. Skibitzke from whom the idea of a possible relationship between the thermal properties of exposed rock type and convectional rainfall in desert watersheds was obtained. Mr. Skibitzke was also responsible for the decision to use solar cells as part of the instrumentation and acted in the capacity of general supervisor throughout the work. I should like to thank Mr. Richard Tinlin of the U.S. Geological Survey in Phoenix for his help in the actual design and construction of the instrumentation and Mr. George Peterson, also of the U.S. Geological Survey, for his invaluable help with the report diagrams and editing. My thanks are extended also to Doctors E. S. Simpson, L. J. Battan, and W. D. Sellers of the University of Arizona for their constructive criticism which has undoubtedly helped to make this report of whatever scientific interest it may be. Last, but understandably not least, I should like to thank my wife Dolores for typing the drafts and final copy of this report.

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ABSTRACT

Radiation from the ground surface into the overlying atmosphere during summertime in Southern Arizona constitutes a major reason for convectional overturn of the moist, unstable air occurring over the state at this time. Radiation = f (T) and for a given rock type in the field,

$$T = g\ (Q_s,\ \alpha,\ \kappa)$$

where

Q_s = incident solar radiation

α = albedo

κ = thermal diffusivity.

The relative quantities of visible energy absorbed by each of the six main rock types occurring in the Harquahala Plains area was measured coincident with measurements of temperature change versus time at 1 inch depth for a day over each of the rock types in question. This data allowed computations of the temperature variation with time in each of the rock types assuming an average daily insolation value for July. Outgoing radiation, ($I_\uparrow$), from each of the rock types was computed from the relationship:

$$I_\uparrow = \sigma T^4$$

where

T = absolute temperature

σ = Stefan's constant.

The greater the magnitude of $I_\uparrow$, then the greater the probability for convectional rainfall to occur. Thus, the relative values of $I_\uparrow$ throughout

the Plain area establish a possible ordered preference for convective rainfall. These values were then compared with rainfall/unit area measured over each of the rock types by radar for one summer rainy season and the results obtained seemed to indicate that for those rock types constituting a significant portion of the total area, a relationship between radiation and rainfall/unit area does exist in that the regions of larger I_t experienced greater rainfall totals per unit area.

INTRODUCTION

The microclimate is a term used by Geiger (1959) to denote the lowest two meters of the atmosphere near the ground. G. Kraus, the father of micrometeorology described it as the "climate in the least space." Large scale variations in temperature take place within this zone. This is illustrated by Sutton (1953) who states, "The climate into which a plant first emerges is quite unlike that experienced by man and the large animals a few feet higher up, for the layer of air within a fraction of an inch of the ground may experience both tropical heat and icy cold in the course of a single day." Temperature variations greater than those normally experienced in the rest of the atmosphere occur throughout the microlayer, both in space and time. The large variations in temperature result from the close proximity of the microlayer to the ground surface. Summer daytime ground surface temperature is normally greater than that in the overlying atmosphere and radiation and conduction from the ground surface into the atmosphere take place. The height to which these processes reach is mainly within the lowermost 100 meters of the atmosphere, although convection and turbulence subsequently move this energy upward into the main body of the atmosphere.

Analysis of the microlayer is complicated by the fact that radiation and conduction across the ground-air interface are temperature dependent processes, and when different bodies are subjected to the same heat source, their temperatures will vary according to properties intrinsic to each. The intrinsic properties upon which temperature response depends are density, thermal conductivity, and specific heat. Albedo also may be regarded an an intrinsic property for purposes of this study, although strictly speaking it is not.

The Harquahala Plains area is composed of some six major exposed rock types, each having a distinct mineral composition and structure. One would, therefore, expect the intrinsic thermal properties of each rock type to be different from those of the others. Hence, under identical conditions of insolation each rock type should be expected to show a different temperature response. And, as mentioned above, since radiation and conduction are temperature dependent, these quantities also should be expected to differ for each rock type.

As stated, radiation and conduction from the ground surface into the overlying atmosphere can cause the temperature of the microlayer to increase. If the temperature of the microlayer is sufficiently increased, atmospheric convection may be initiated.

In general, the cause of convective currents in the atmosphere has long been recognized as the result of instability created in a relatively cool air mass passing over a warmer water surface or passing over some portion of the earth's surface that has been warmed through solar radiation. Once the lapse rate of the environment equals or is greater than that of the dry adiabatic lapse rate, any heating of an air mass near the earth's surface will result in its vertical ascent accompanied by a temperature change of the ascending air mass at the dry adiabatic lapse rate until condensation occurs or the air mass reaches a stable position aloft. If continued uplift persists through thermal heating at the ground surface and enough moisture is present in the air, a cumulo-nimbus cloud, or thunderhead, will result (Trewartha, 1954).

Most certainly, solar heating of the ground surface and the resulting thunderhead activity is one of the main sources of Southern Arizona's summer rainfall. In this area, extreme convective overturn would probably begin sometime in May or June, although the moisture content of the air would not be sufficient to support precipitation until early or mid July.

Since radiation from the ground surface into the atmosphere represents one of the major reasons for convectional overturn in the atmosphere, it seems logical to assume that by establishing the relative thermal characteristics of a particular basin, the preferential areas for convectional overturn could be established, if they exist. Figures 1 and 2 are photographs of apparently preferential cloud build up photographed in the Harquahala Plains area during August, 1963.

It is the purpose of this report to try to establish, in a relative sense, the thermal characteristics of the major rock types exposed at the surface in the Harquahala Plains area with regard to the energy contained within the visible portion of the solar spectrum and to discuss what possible effect these thermal characteristics might have had on the rainfall distribution as recorded for one summer rainy season in the Harquahala Plains area.

Figure 1.--Mid-morning Development of Cumulus Over Low Hills of Andesitic Composition - Surrounding Lowlands Mainly QTs

Figure 2.--Mid-afternoon Development of Cumulus Over Quaternary-Tertiary Sands, Gravels, and Conglomerates - Hills to Right Mainly Granitic In Composition

LOCATION AND CLIMATE

The Harquahala Plains area is located in the southwestern portion of Arizona occupying a large portion of the area between Buckeye and Salome, Arizona (Fig. 3). It consists of a large intermountain valley, maximum width approximately 15 miles, bordered by five mountain ranges.

The valley is flanked on the north by the Big Horn and Saddle Mountains, and the Gila Bend Mountains occur on the extreme southeast portion of the valley. The Little Harquahala Mountains flank the valley on the west, and the Harquahala Mountains are situated on the northwestern portion of the valley. Although these ranges are classed as mountains, they actually are little more than desert hills, since with the exception of the Harquahala Mountains, their actual relief is not too excessive, ranging from approximately 1,400 feet at their base to 3,360 feet at their maximum elevation. The Harquahala Mountains, on the other hand, reach heights of some 5,720 feet.

Centennial Wash, an intermittent stream, enters the Plains through a small valley between the Little Harquahala Mountains and the Harquahala Mountains on the northwestern side of the Plains area and leaves it through the southeast corner to eventually flow into the Gila River, some 20 miles or so to the southeast.

Vegetation on the mountains is scarce and consists chiefly of sparsely scattered barrel cactus, palo verdes, ocotillo, mesquite, and other general desert flora. Within the valley itself, and particularly within the confines of Centennial Wash, vegetation becomes much thicker,

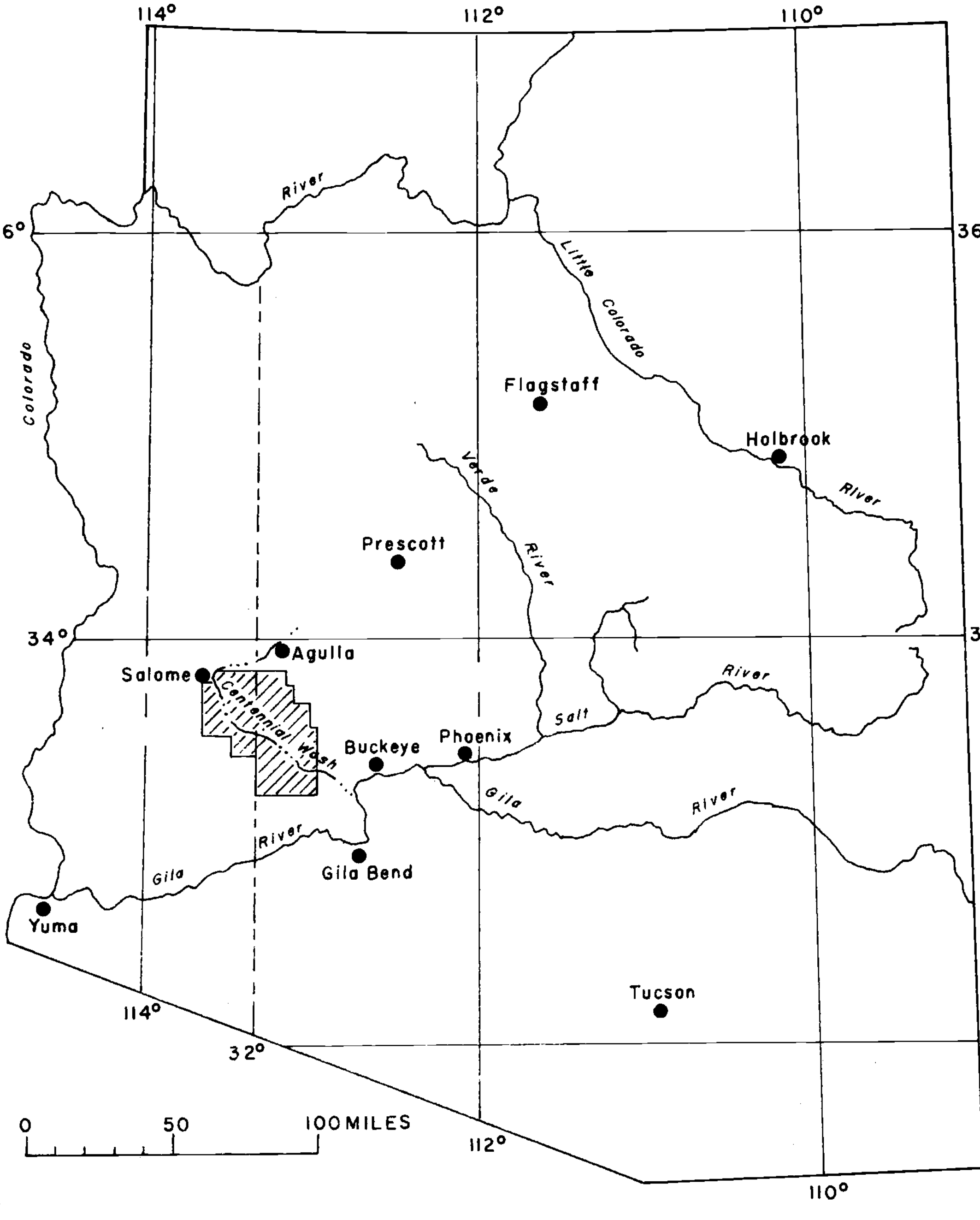

Figure 3. Map of Arizona Showing Harquahala Plains Area, Arizona

consisting mostly of iron wood, palo verde, and mesquite trees. In December, 1963, approximately 33,000 acres in the lower Harquahala Plains were under cultivation, the major crop being cotton.

Generally, the Harquahala Plains area is considered to lie within an arid climate. Average annual rainfall throughout the valley is less than 10 inches per year. Daily temperature ranges are likely to be more excessive than annual as is common for a climate of this type. Diurnal temperature fluctuations range from mean highs around $105^{\circ}F$ to mean lows around $70^{\circ}F$ in the summer months. Annual monthly ranges are from mean highs around $90^{\circ}F$ to lows around $50^{\circ}F$.

There are two distinct periods of precipitation recognized in Southern Arizona - the winter rainy season and the summer rainy season. The first occurs during November to March, when the area is subjected to occasional storms from the Pacific Ocean. While this is classed as a rainfall season, there can be periods of a month or more when little or no precipitation will occur. The second rainfall period occurs during July, August, and September when all of Arizona is subjected to widespread thunderstorm activity with moisture supply originating in the Gulf of Mexico.

The spring and fall months are generally dry, although precipitation in considerable amounts has been known to occur.

SUMMER PRECIPITATION CHARACTERISTICS

Throughout most of Arizona, the months of July, August, and September are characterized by the high precipitable water available in the atmosphere and by the relatively high rainfall totals received. July and August represent the two months of greatest rainfall for Southern Arizona.

The main features of an area's rainfall pattern can be explained through consideration of the area's geographic location with regard to the major pressure systems of the earth and sources of moisture. Bryson and Lowry (1955) and Jurwitz (1953) discuss the rainfall features of Southern Arizona from this point of view. Only a brief summary will be given in this section.

It is well known that pressure systems have a distinct effect upon precipitation. In general, a region of low pressure would be an area conducive to rainfall while a region of high pressure would not be. Furthermore, the subsidence and divergence of air in a high-pressure system is greatest on the eastern flank of the high-pressure cell. This renders the air masses in this region very stable; and as a result, there is little or no precipitation in any region influenced by these factors. On the western portion of a high-pressure system, the subsidence and divergence is not as marked, and here the air of the anticyclone is characteristically moist and unstable, resulting in abundant precipitation.

Bryson and Lowry (1955) have shown that a rather abrupt change in air masses occurs over Arizona around the first of July. Their studies showed that in late June to early July, the Pacific subtropical anticyclone shifts from around 38° to 41°N latitude. Accompanying this movement is the penetration into the state of deep, moist, gently-flowing air from the Gulf of Mexico on the southwest side of the western portion of the Bermuda High (Figs. 4 and 5). The penetration of this air mass would account for the relatively high values of precipitable water present in the atmosphere at this time since the air mass would have traveled for some time over the waters of the Southern Atlantic Ocean and Gulf of Mexico before reaching Arizona. The air mass is both moist and unstable then, but this in itself will not cause precipitation. There must be some means for providing vertical uplift of the air to the extent that its temperature is reduced below the dew point, thus causing condensation and precipitation to occur.

Bryson (1957) states that summer rainfall in the Tucson area cannot be approached from a frontal analysis, but is the result of local convergences acting upon the penetrating air mass from the Gulf of Mexico. He tabulated measurements of wind direction at 500 mb and rainfall experienced at Phoenix during July and August, 1950-53. From these measurements, he was able to show a distinct relationship between southeasterly winds and convectional rainfall experienced at Phoenix.

For the most part then, vertical uplifts of the air over Southern Airzona during the summer occur as a result of the heating of the air at the ground surface, causing it to expand and thereby being forced to rise by the cooler, heavier air surrounding it. The heated air will continue to rise until its temperature and density are the same as the surrounding air; or if condensation occurs before this happens, there

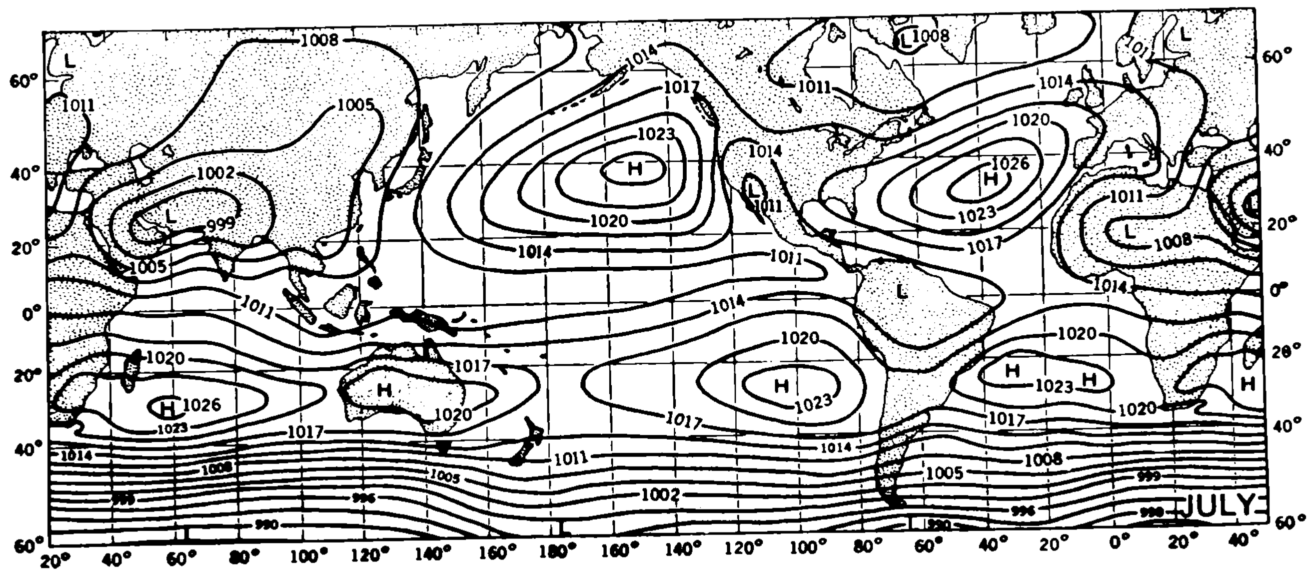

Figure 4.--July Mean Sea Level Pressure in Millibars (After Mintz and Dean)

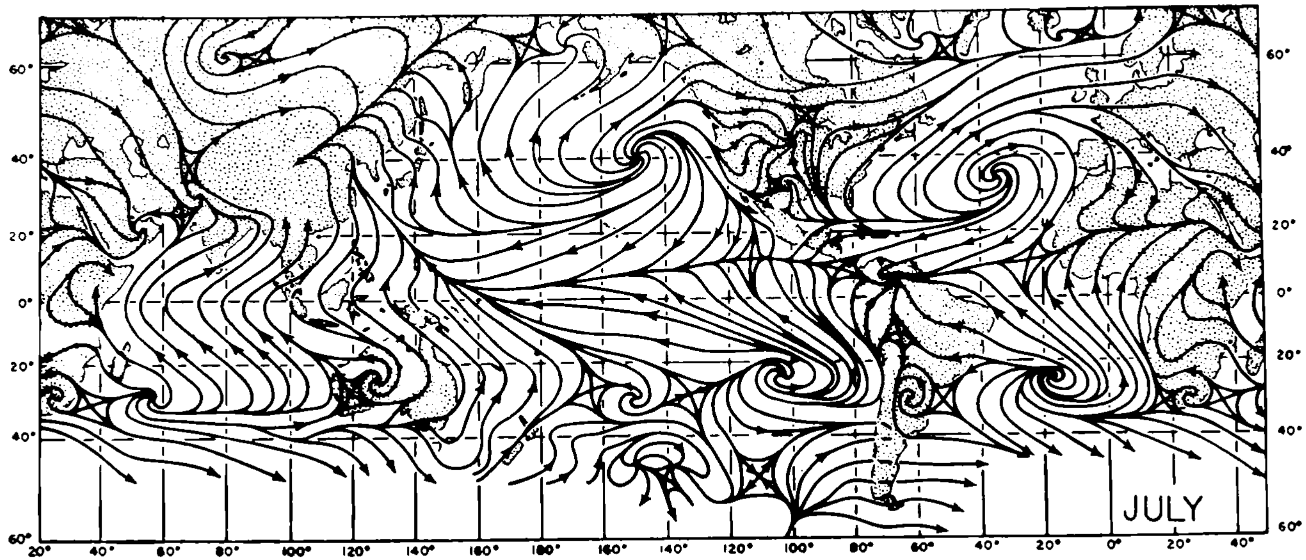

Figure 5.--July Direction of Mean Surface Resultant Wind (After Mintz and Dean)

will be an additional source of energy causing further ascent of the air mass to occur.

EXPOSED ROCK TYPES

The rocks exposed within the Harquahala Plains area may be divided into eight major types: Pre-Cambrian granitic gneiss, p€gn; Pre-Cambrian schist, p€s; and Pre-Cambrian granite, p€g; Paleozoic-Mesozoic undivided, PMu; Cretaceous andesite, Ka; Quaternary-Tertiary sand, gravel and conglomerate, QTs; Quaternary basalt, Qb; and finally Quaternary sands and gravels, Qs.

The major portion of the valley is composed of Quaternary sands and gravels laid down by Centennial Wash, and Cretaceous andesite constitutes the major rock type exposed in the mountains. Locally there are dikes and plugs of Cretaceous age, but these occupy only small areas of the mountains. Metzger (1957) states that Pre-Cambrian rocks occur in every mountain block surrounding the Harquahala Plains, the predominant rock type being granitic gneiss; other units are gneiss, schist, and granite.

The Big Horn and Saddle Mountains that border the valley on the north and northeast respectively, are composed chiefly of Cretaceous andesite. The northwestern portion of the Big Horn Mountains, however, is composed mainly of granitic gneiss. The Eagle Tail Mountains that flank the Plains on the south, consist of Quaternary basalt, Cretaceous andesite, dikes and plugs of Cretaceous age, and finally of Pre-Cambrian granitic gneiss and granite.

The Harquahala Mountains on the northwest side of the Plains consist chiefly of Pre-Cambrian granitic gneiss, along with a mixture of Laramide granitic and related crystalline rocks and a rather large area of rock units denoted as Paleozoic-Mesozoic Undivided. These latter consist chiefly of shale, quartzite, and limestone.

The composition of the Little Harquahala Mountains on the western extremity of the valley will not be considered since in this area, the areal and time distribution of rainfall was not recorded. The last statement is true of the Harquahala Mountains also.

Since the author was interested only in the thermal characteristics of the more general rock types, little work of a geologic nature was carried out for this report. Accordingly, the above information is based chiefly upon the geologic maps for Maricopa and Yuma Counties, published by the Bureau of Mines, Tucson, Arizona, and a report by D. G. Metzger of the U.S. Geological Survey "Geology and Ground-Water Resources of the Harquahala Plains Area, Maricopa and Yuma Counties," 1957, U.S. Geological Survey open-file report.

Those rock types over which measurements were made were chosen solely on the basis of their areal extent in the Harquahala Plains. On this basis, it was decided to run the instruments over: (1) Pre-Cambrian gneiss; (2) Pre-Cambrian granite; (3) Pre-Cambrian schist; (4) Cretaceous andesite; (5) Quaternary-Tertiary sand, gravels, and conglomerate; (6) Quaternary basalt; and (7) Quaternary sands and gravels. Instrumentation difficulties prevented setting up over the Pre-Cambrian gneiss, however, thus measurements were made only over the remaining six rock types.

THEORY

That energy reaching the earth's atmosphere from solar radiation is generally denoted as insolation. The major portion of this energy is contained between the wave lengths 0.15μ and 4.0μ. According to Fowle (Brunt, 1952) on a clear day with the sun in the zenith, the total loss from the solar beam due to absorption in the atmosphere down to sea level is only about 6 to 8 per cent of the incident radiation. Thus, on a clear day, by far the greater part of solar radiation passes unchanged through the earth's atmosphere and is either absorbed by or reflected upward from the earth's surface (assuming no energy used for evaporation). Clouds, when present, absorb and reflect large portions of the solar beam, thereby reducing significantly that energy reaching the ground surface.

The ratio of solar insolation reflected by the ground surface to the total insolation reaching it, is known as the ground-surface albedo. The albedo will change as the characteristics of the ground surface change. Changes in vegetation, water, color, and surface roughness are among the most important variables. Magnitude and direction of surface slope will also affect albedo as well as wave length distribution of insolation.

That portion of insolation absorbed by the ground surface will cause its temperature to rise. The temperature of each rock type at any particular depth will, in general, differ one from the other since the rate of change and final temperature reached by each rock type is dependent both on the energy available to it and its own inherent thermal properties. The ground-surface albedo will play a major role in energy available to each rock type; for instance, if two rock types are subjected to the same insolation and have different surface albedos, the rock type with the lowest albedo will absorb more energy. This would mean that even if the thermal properties of both rock types were the same - one would reach a higher temperature than the other.

The ground surface radiates energy back into the atmosphere, and this energy is composed of wave lengths which the atmosphere is capable of absorbing to a large extent, thereby raising its temperature. The rate at which the ground radiates energy into the atmosphere depends primarily on the ground temperature, so that if this varies over a given area, other things being equal, a temperature difference in the overlying air will result. A density or pressure gradient in the lower atmosphere is thus established, causing the heavier air to displace the lighter air upward, representing the beginning mechanism of convectional overturn.

Those factors that affect the magnitude of surface albedo varied over the Harquahala Plains area and varied within each rock type. Also, it is not to be expected that the thermal properties of a rock type encompassing a large area will remain homogeneous throughout. These and other factors as well make it difficult to arrive at any complete understanding of the areal and time distribution of convectional rainfall. For purposes of this investigation, measurements were made for each of the various rock types where (a) slope was essentially horizontal, and (b) vegetation and moisture were absent. The results of the measurements were generalized for the entire area. The theory described in the pages which follow, takes into account the considerations mentioned above.

Solar Radiation

On a year-to-year basis, measurement has shown that the amount of incoming solar energy reaching the outer limits of the earth's atmosphere has remained nearly constant. The amount of energy incident on a given surface in the outer limits of the earth's atmosphere varies only with season and latitude, while the annual totals it receives are nearly always equal (Berry, Bollay, and Beers, 1945).

Measurement has also shown that the spectral distribution of solar radiation closely approximates that of a black body. From Boltzman's law and by knowing the flux of energy at the outer limits of the earth's atmosphere, it is possible to approximate the temperature of the sun necessary to produce this flux. Calculations have shown this temperature (known as the effective temperature of the sun) to equal $5{,}760^{\circ}K$. From Planck's law, it can be shown that a black body at the sun's temperature would radiate nearly 99 per cent of its energy between wave lengths (λ), $0.15\mu \leq \lambda \leq 4\mu$. Between these extremes, some 9 per cent has a wave length, $\lambda < 0.4\mu$; 45 per cent has wave length, $0.4 \leq \lambda \leq 0.74\mu$; and 46 per cent lies in the range, $\lambda > 0.74\mu$ (Berry, Bollay, and Beers, 1945).

This does not mean, however, that any given surface at ground level would experience this same spectral distribution. In passing from the outer limits of the earth's atmosphere to the ground surface, solar radiation undergoes some four processes which deplete the total amount and kind of energy reaching the surface. These processes consist of (1) absorption by ozone in the upper atmosphere of the earth - this process eliminates wavelengths below 0.29μ and depletes approximately 5 per cent of the total incoming energy; (2) scattering by dry air; (3) absorption, scattering, and diffuse reflection by solid particles; and (4) absorption and scattering by water vapor. The ability of each process to deplete incoming energy varies from place to place, except that the first is fairly constant.

Upon reaching the surface, the remaining energy is either reflected or absorbed by the ground - the relative amounts of each being a function of the wavelength reaching the surface and the albedo of the ground.

On an annual basis, that amount of energy absorbed by the ground must be given up by the ground if steady-state conditions are to exist. On a daily basis, however, more energy may be absorbed than given up by the ground or vice versa.

That portion of energy which is reflected at the ground surface will move upward through the atmosphere being subject to the same processes that operated on its movement down toward the ground surface. This energy will cause only negligible heating of the air mass immediately overlying the ground surface since it will be mostly composed of wavelengths that the air mass cannot absorb, i.e., short wavelengths.

As the ground absorbs energy, its temperature rises, and it will radiate energy into the overlying air mass at greater rates as heating continues. If the temperature of the ground surface is raised so that it is much greater than that of the overlying air mass, conduction from the ground to the air becomes large in its own right. It is the combination of radiation and conduction from the ground surface into the microlayer that raises the temperature of the microlayer to such an extent that instability occurs resulting in convectional overturn of the atmosphere.

To proceed further, it becomes necessary to examine the processes by which the earth obtains and loses energy.

Energy reaching the ground during daylight hours will come from the following three main sources: (1) direct beam solar radiation that has traveled from the outer limits of the atmosphere to the ground surface; (2) energy known as diffuse radiation resulting from the diffusion of direct beam-solar radiation by small particles contained within the atmosphere; and (3) radiation from the atmosphere itself, since as a result of its absorption of solar energy, the atmosphere is radiating energy in all directions. These three processes constitute the main sources of energy reaching the ground surface. There is a fourth means by which energy may reach the ground surface - that of conduction. During daylight hours of the summer, however, when the ground is normally heating, ground-surface temperatures are usually greater than overlying air temperatures, so that conduction at this time is generally from the ground into the air.

If the total rate at which energy is reaching the ground is denoted as E_q, we may write

$$E_q = Q_s + I_\downarrow + q + H_\downarrow \tag{1}$$

where

Q_s = direct beam solar radiation

$I_\downarrow$ = counter radiation from atmosphere to the ground surface

q = diffuse radiation

$H_{\downarrow}$ = conduction from air to ground surface.

Those processes by which the ground may lose energy consists of (1) the reflection of incident solar energy, (2) radiation, and (3) conduction. If this energy is denoted as E_L, we may write

$$E_L = (Q_s + q)\,\alpha + I_{\uparrow} + H_{\uparrow}, \tag{2}$$

where α equals albedo of the ground surface.

If each of these quantities is measured as a rate, the energy represented by $E_q - E_L$ would constitute the rate at which energy was absorbed at the ground surface at the time of measurement. If considered for any given period of time, Δt, then $(E_q - E_L)\,\Delta t$, would represent the energy absorbed at the ground surface for that period. Thus,

$$E_q - E_L = (Q_s + q)\,(1 - \alpha) - I - H \tag{3}$$

where

$I = I_{\uparrow} - I_{\downarrow}$,

$H = H_{\uparrow} - H_{\downarrow}$.

The quantity $(Q_s + q)\,(1 - \alpha) - I$ is referred to by meteorologists as the net radiation, generally denoted as "R."

Neglecting conduction, it can be seen that the energy absorbed by the ground is equal to R, or if conduction is considered, the energy absorbed by the ground for any instant of time is given by $R = H + G$

R = net radiation

G = energy absorbed by the ground equals $E_q - E_L$

H = $H_{\uparrow} - H_{\downarrow}$.

INSTRUMENTATION

A system of solar cells was devised capable of detecting the energy within the visible portion of the solar spectrum. The solar cells were contained within two racks, each rack consisting of three solar cells. Gelatin and glass filters were placed over the solar cells in each rack, allowing only certain wave length spans to be measured (Fig. 6). One rack faced toward the sky and the other toward the ground surface. By means of the first rack, it was possible to measure that portion of E_q contained within the visible portion of the spectrum, and the visible portion of energy representing E_L was measured with the second rack.

The design of the equipment was based upon the following considerations. First, measurement of that energy contained within the visible portion of the solar spectrum presently represents one of the few means of measuring hydrologically significant factors on a regional basis by aerial photography or remote sensing (Skibitzke, oral communication). Thus, it was desired to determine whether or not correlation might exist between the temperature increase in various rock types and the visible energy available to them for absorption. If the measurement of this portion of insolation represents an index to the temperature increase in various rock types, it would be extremely useful for future hydrologic studies, since this energy band is easily measured.

The solar cells were connected electrically through a switching device to an Esterline Angus recording ammeter and were set at a height of about 1 meter over each of the six rock types previously mentioned. Measurements of incoming and outgoing energy were recorded at each location for a period of 24 hours. Figures 7 to 9 show the incoming and outgoing energy versus time, and table 1 gives the values of these recordings as well as the wavelengths each recording represents. The values in table 1 represent area as measured by a planimeter under the curves shown in figures 7 to 9.

There were two types of solar cells used - the selenium photocell and the silicon solar cell. The former type has an approximate output in sunlight of 0.33 to 0.40 volts and 1.50 to 2.50 ma, while the latter has an approximate output in sunlight of 0.33 to 0.45 volts and 10 to 16 ma. Both represent a means for the direct conversion of the visible portion of sunlight into electricity.

The amperage output of each solar cell is directly related to the intensity of radiation, but the output was not converted to units of solar radiation such a ly/minute, since only relative characteristics of the various rock types are to be considered. Hence, the data obtained are plotted as amperage versus time for each wavelength span and each rock type. The area under each curve thus produced is, therefore, a measure of total energy. (See following table.)

Table 1.--Relative Values[a] of Incoming and Outgoing Energy for a 24-Hour Period Over Selected Rock Types in Harquahala Plains Area, Arizona

Wavelength λ	QTs		Qs		p€s		p€g		Qb		Ka	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
0.300-0.515μ	0.750	0.650	0.705	0.652	0.782	0.609	0.708	0.645	0.819	0.674	0.734	0.624
0.510-0.605μ	0.175	0.087	0.188	0.100	0.218	0.098	0.186	0.089	0.245	0.110	0.214	0.073
0.605-0.750μ	0.302	0.128	0.320	0.158	0.309	0.129	0.248	0.117	0.352	0.117	0.316	0.110
Total	1.227	0.865	1.213	0.910	1.309	0.836	1.142	0.851	1.416	0.901	1.264	0.807

a. Given by area under curves figures 7 to 9.

At the same time that the rate of incoming and outgoing energy was being recorded, the temperature of the ground was being recorded by means of a thermistor placed at 1-inch depth. A small 1.4-volt battery (Eveready Mercury Energizer, No. E9) was used as a current source. The battery and thermistor were then connected electrically with the Esterline Angus recording ammeter through the same switching device as was used with solar cells (Fig. 6).

Measurement of temperature at the actual ground surface is a complex task and not essential for the purpose of this report. Temperatures recorded at 1-inch depth will be used instead. The temperature at this depth will be a function of the magnitude of the incident-solar energy, the ground-surface albedo, and the thermal diffusivity of the ground. Figures 10 to 12 give the results of these measurements.

It was imperative that the conductivity of the hole in which the thermistor was inserted was less than the surrounding rock. An epoxy coating was, therefore, put around the thermistor and connecting wire. The diameter of the coating was just under the hole diameter into which the thermistor was inserted. Spun glass was inserted at the top in the space between the rock wall and epoxy. This was then covered by more epoxy which was spread over the top of the hole to further reduce radiation and conduction into the hole. The hole diameter into which the thermistor was placed was three-eighths of an inch.

By the processes described above then, it was possible to monitor the incoming and outgoing solar energy within the visible portion of the incident solar spectrum for each of the rock types and to record the change of temperature with time at a depth of 1 inch in the rock.

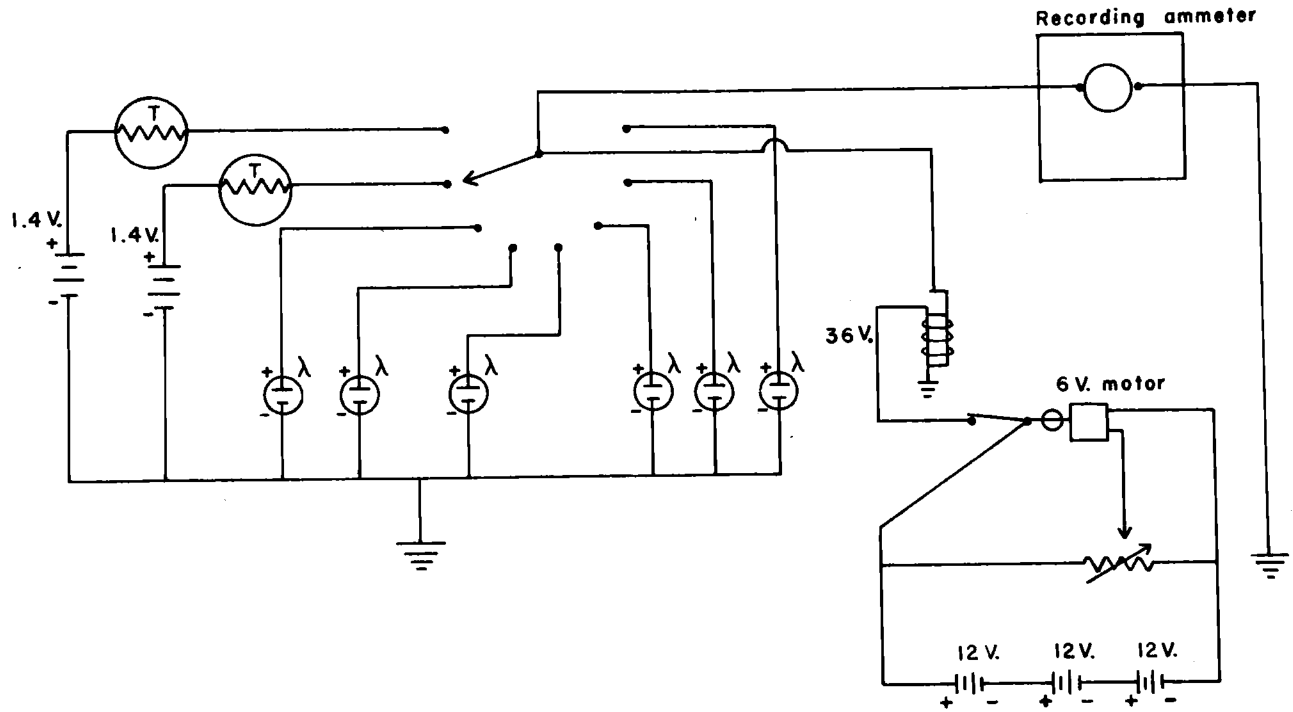

Figure 6.--Schematic Diagram of Field Instrumentation

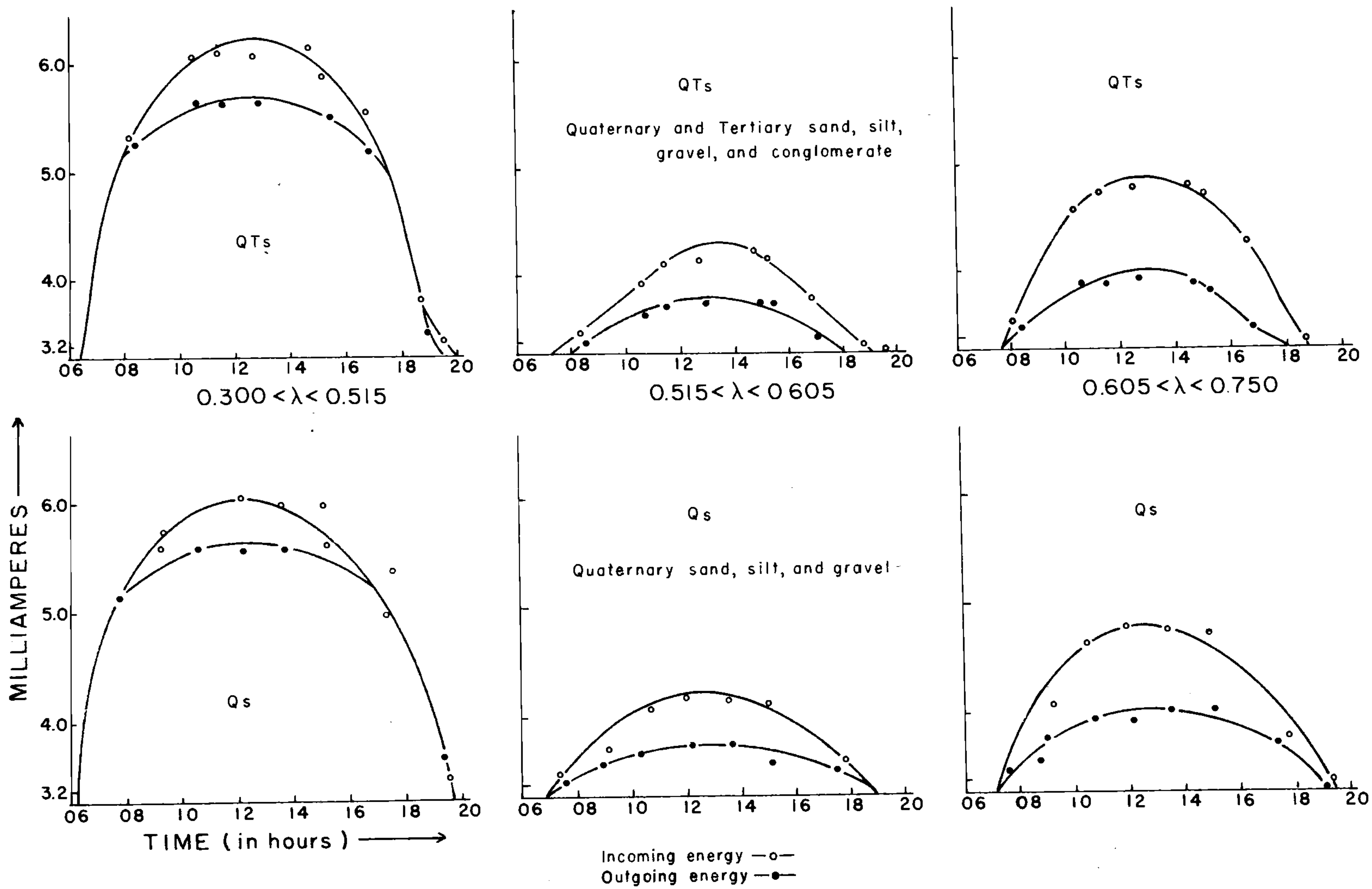

Figure 7.--Curves Showing Measured Incoming, E_G, and Outgoing, E_L, Energy Within The Visible Portion of The Solar Spectrum Versus Time in QTs and Qs (Energy Assumed Proportional to Current)

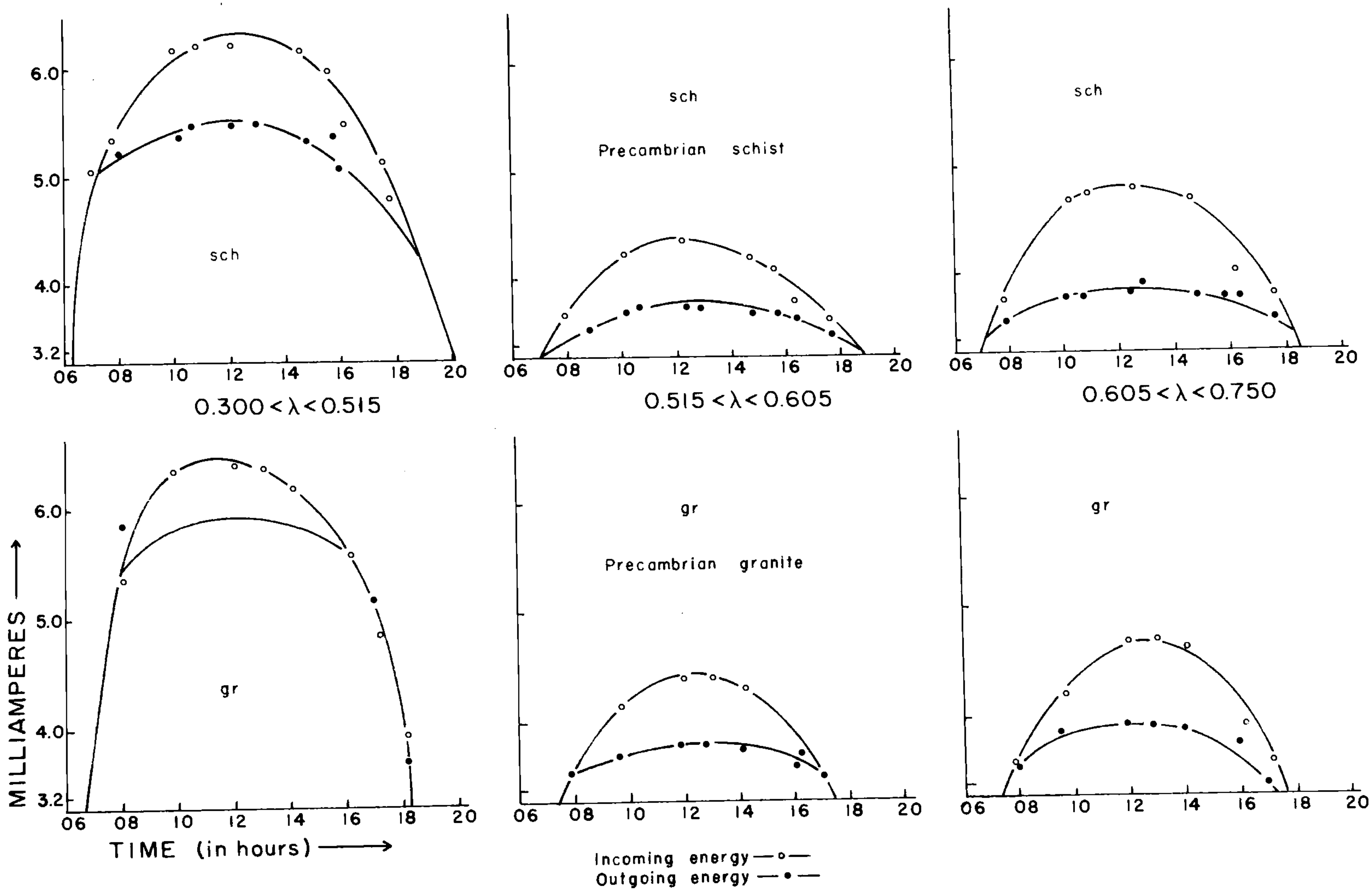

Figure 8.--Curves Showing Measured Incoming, E_q, and Outgoing, E_L, Energy Within The Visible Portion of The Solar Spectrum Versus Time in p€s and p€g (Energy Assumed Proportional to Current)

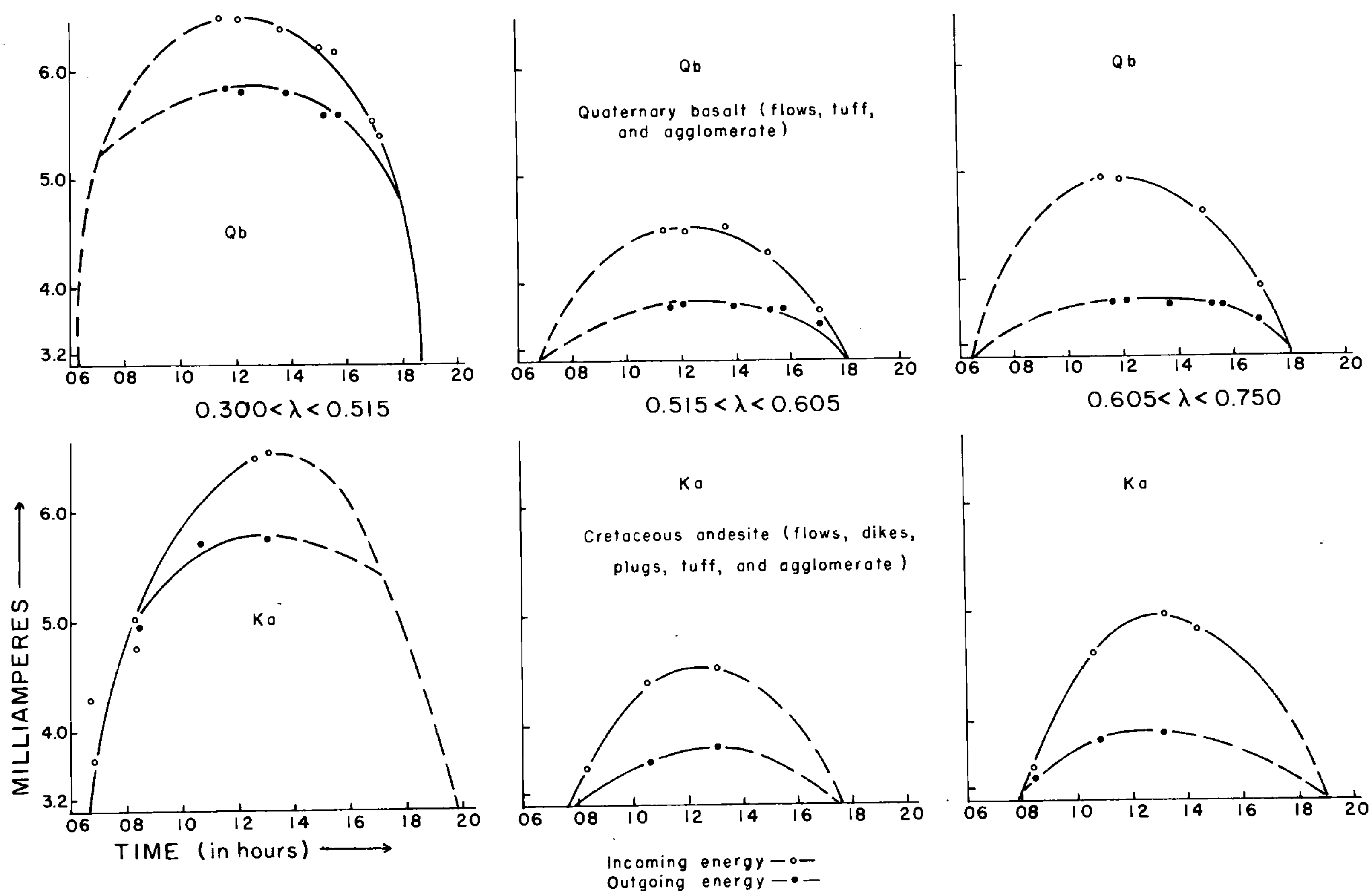

Figure 9.--Curves Showing Measured Incoming, E_q and Outgoing, E_L, Energy Within The Visible Portion of The Solar Spectrum Versus Time in Qb and Ka (Energy Assumed Proportional to Current)

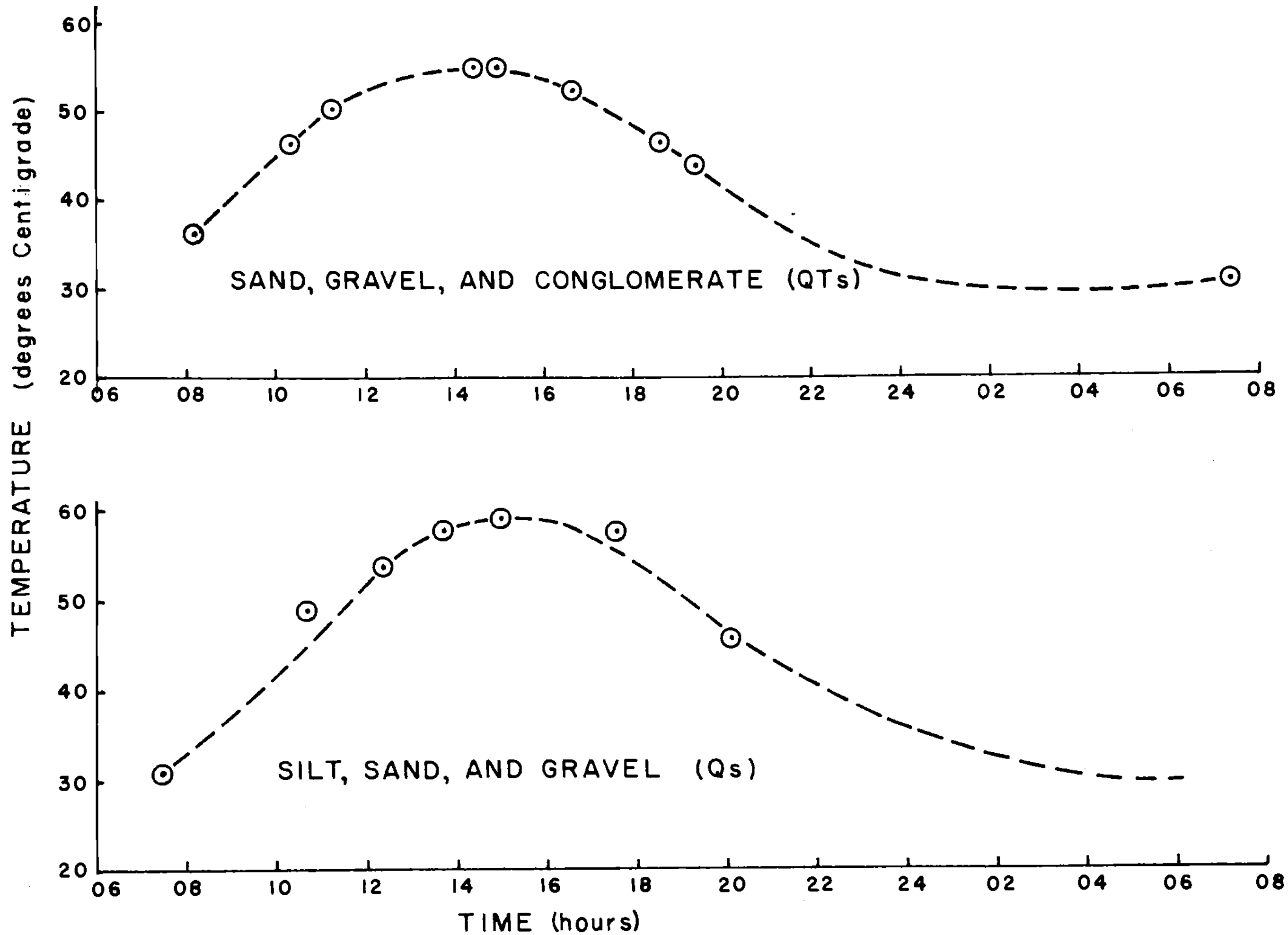

Figure 10.--Temperature Variation With Time at 1 Inch Depth Below Ground Surface in QTs and Qs

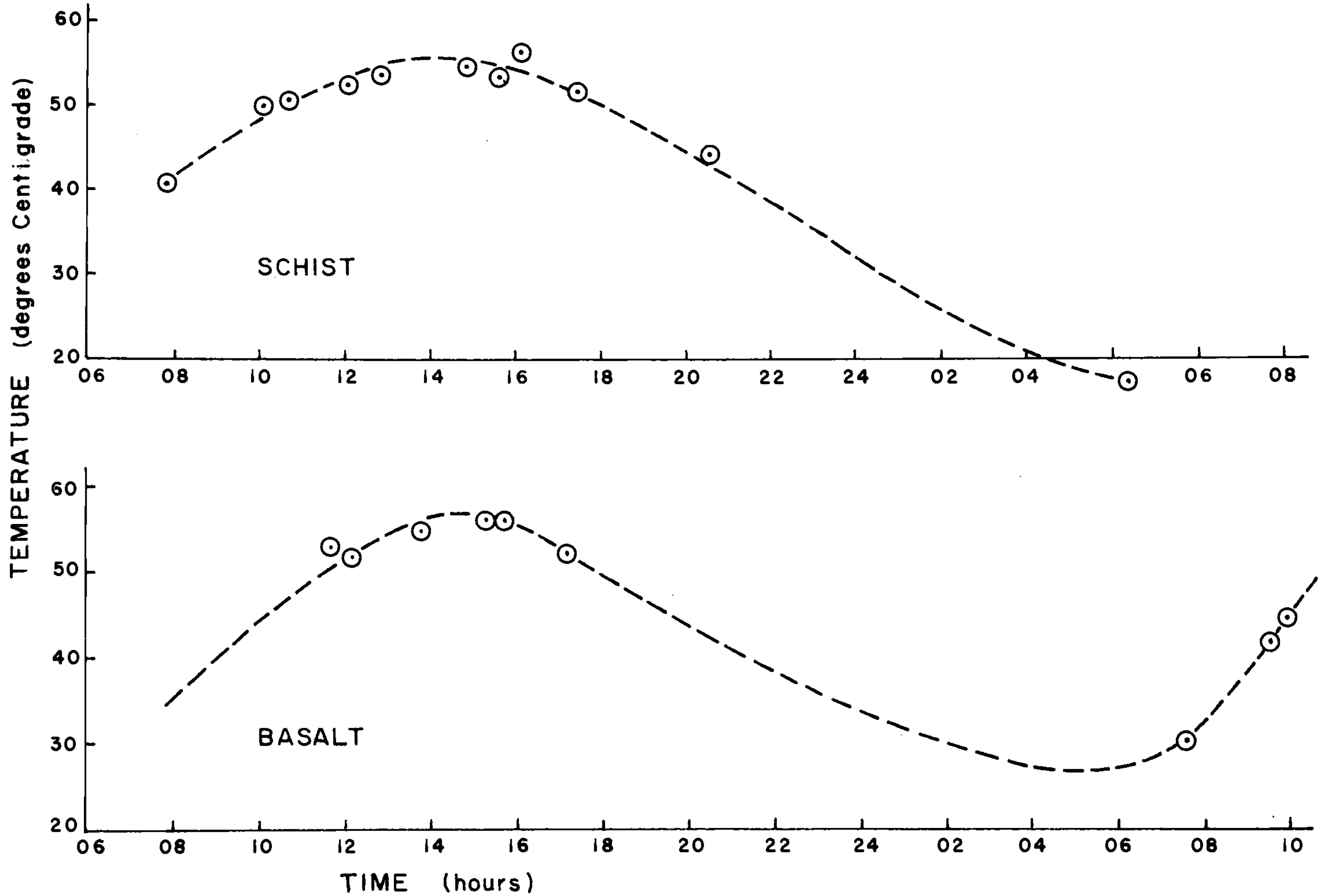

Figure 11.--Temperature Variation With Time at 1 Inch Depth Below Ground Surface in p€s and Qb

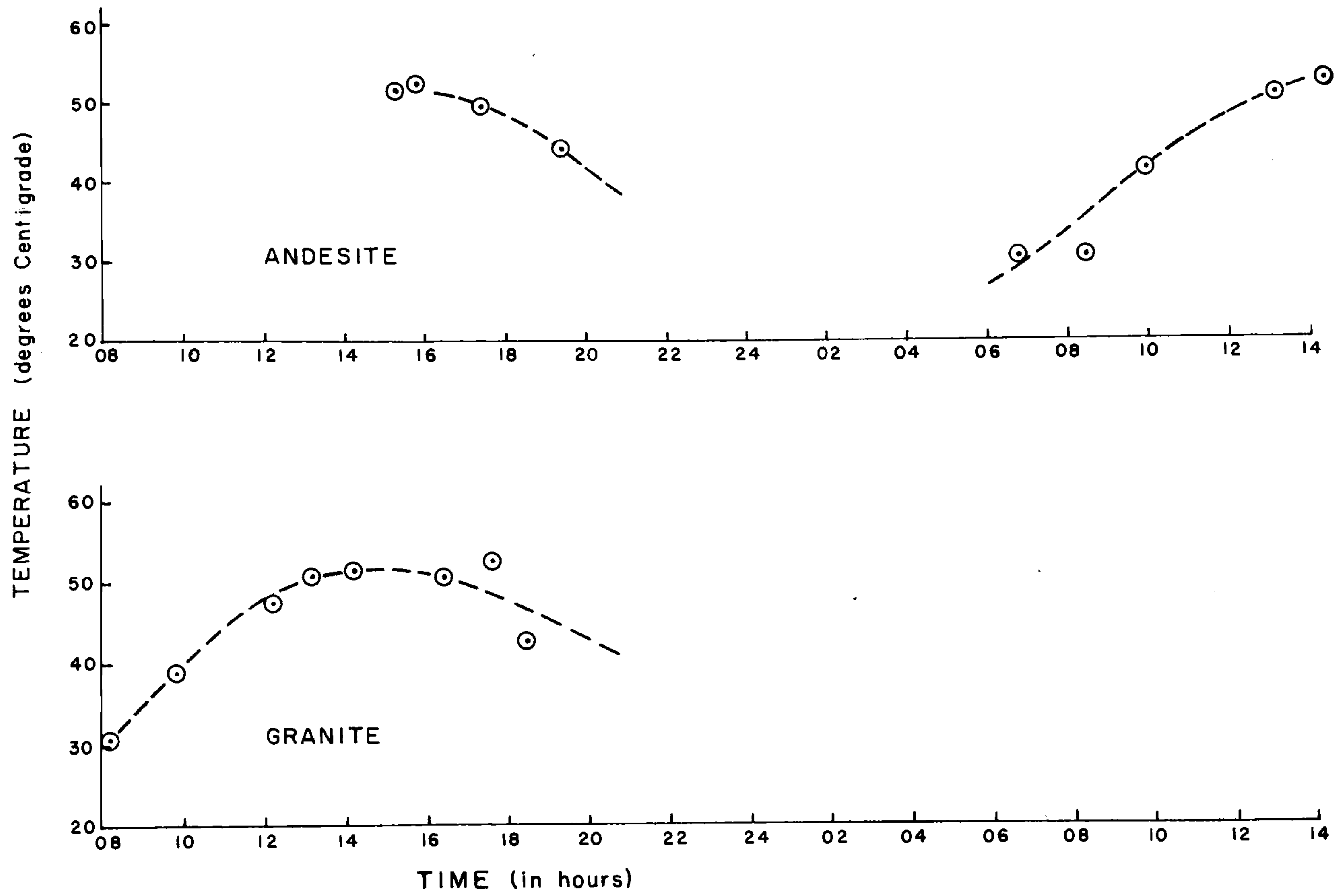

Figure 12.--Temperature Variation With Time at 1 Inch Depth Below Ground Surface in Ka and p-g

ENERGY CONSIDERATIONS AT THE GROUND SURFACE

The ground surface is exposed to a harmonic variation in insolation on both a diurnal and an annual basis as a result of the rotation and revolution of the earth about the sun. The response of the ground to this harmonic variation in insolation is shown by the sinusoidal temperature variation which it undergoes on a diurnal basis. With regard to radiation from the ground surface into the atmosphere, it is the maximum temperature reached by the ground surface that is of interest as will be shown later. Lettau (1951) has gone through an analysis of the oscillations and amplitude of temperature reached near a level ground surface from considerations of the components of the heat balance equation (p. 20) and his basic assumptions and conclusions will be recounted here. He assumes a ground material homogeneous with respect to its thermal characteristics and one in which there is no change with time in the magnitude of these properties. The rate of evaporation from the surface is considered constant. Lettau examines the flux of insolation being transferred by conduction from the soil-air interface into the soil and the flux of energy moving upward from this interface by turbulent processes. Upon taking the time rate of change of these two fluxes, he obtains two basic equations that can be solved in order to arrive at the functional relationship between the amplitude of the ground surface temperature and its thermal properties. In solving these equations, five basic initial and boundary conditions are assumed. First G and H (p. 20) approach zero at all times for large depths and heights; second, for $Z = 0$, temperature is continuous at all times; third, at $Z = 0$, $R = R_o$ which is a given harmonic of time; fourth, evaporation is a constant $= E_\infty$; and fifth, at $Z = 0$, $R_o(t) - E_\infty = \left\{G\ (-Z,t) + H\ (Z,t)\right\}_o$ where t = time and the subscript indicates the ground surface.

The final result is that the amplitude of the ground surface temperature is given by

$$\Delta T_o = \left(\frac{\pi a_o}{\theta' c_p \rho_a}\right) \sqrt{j^2 + \tfrac{1}{4}} \qquad (4,a)$$

$$\Delta T_o = \frac{b_o}{\rho_s c} \sqrt{\nu \kappa} \qquad (4,b)$$

where

ΔT_o = amplitude of temperature at the ground surface

$\theta' = \frac{\partial \theta}{\partial Z}$; θ = eddy diffusivity of air

c_p = specific heat of air

ρ_a = density of air, ρ_s = density of ground material

j = dimensionless function of turbulence

c = specific heat of ground material

ν = frequency of the harmonic oscillation of insolation

κ = thermal diffusivity of soil $= \frac{K}{\rho c}$

a_o = amplitude of the oscillations of flux into the air at the ground-air interface

b_o = amplitude of the oscillations of flux into the ground at the ground-air interface

Lettau states then, "that for given atmospheric conditions, ground types having a large value of the thermal property parameter $\rho c \sqrt{\kappa} = \sqrt{\rho c K}$ (β-function) tend toward an equable microclimate. The portion of radiational energy utilized in heating the air is small compared with that utilized in heating the soil."

Components of Energy Lost at the Ground Surface (E_L)

Energy lost by the ground surface has been previously defined by equation 2. In order to determine what the solar cells facing downward are being subjected to, each component of this equation needs to be more carefully examined. The first term, α $(Q_s + q)$ will contain wave lengths extending from ultraviolet through infrared. Since the solar cells were only capable of detecting those wave lengths contained within the visible portion of the spectrum, the energy described by α $(Q_s + q)$ actually refers only to this portion of the spectrum. Thus, α is for the visible portion of the spectrum only with regard to measured outgoing energy and from here on it shall be denoted as α_v.

Conduction, H, is a process that arises from the elastic impact of molecules, without any net transfer of matter, and the subsequent transfer of this energy upward by convection are processes of energy transfer that would not be detected by the solar cells.

Radiation ($I_{\uparrow}$) consists of the transfer of energy by electromagnetic waves. The surface of the earth may be considered a black body at approximately 300°K, and it follows from the laws of Planck and Wein that the maximum intensity of wave length emitted occurs at about 10μ and for most practical purposes, the entire spectrum of emission is contained within the wave lengths between 3 and 80μ (Brunt, 1952).

The energy radiated per unit time from a unit surface can be computed from Stafan's law (which assumes a black body) as follows (Brunt, 1952):

$$I_{\uparrow} = \int_0^{\infty} E_{\lambda} d\lambda = c_1 \int_0^{\infty} \frac{\lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1} d\lambda$$

which yields upon integration

$$I_{\uparrow} = \sigma T^4 \qquad (5)$$

where

σ = Stefan's constant

E_λ = energy emitted per unit area per unit time within unit range of wave length centered on λ.

T = absolute temperature

λ = wave length

c_1 = constant

c_2 = constant.

It is possible to identify the wave lengths composing I , and calculations show that there is negligible energy contained within the visible portion of the spectrum for material at those temperatures measured in the field.

Thus, it can be seen that the energy lost by the ground surface and detected by the instrumentation consists solely of α_v $(Q_s + q)$, or

$$E_L' = \alpha_v (Q_s + q) \qquad (6)$$

or

$$\alpha_v = \frac{E_L'}{(Q_s + q)} = \frac{\text{area of back curve}}{\text{area of incoming curve}} \qquad (7)$$

From equation 7 and the discussion preceding it, the albedos for the visible portion of the solar spectrum are computed in column 4, table 2. These values are high when compared to previously measured albedos for this part of the spectrum.

Table 2.--Visible Light Albedos and Absorption Percentages for Selected Rock Types, Harquahala Plains, Arizona

Rock type	Energy in[a]	Energy out[a]	α_v (per cent)	$(1-\alpha_v)$
QTs	1.227	0.865	70.5	29.5
Qs	1.213	0.910	75.0	25.0
p€s	1.309	0.836	63.9	36.1
p€g	1.142	0.851	74.5	25.5
Qb	1.416	0.901	63.6	36.4
Ka	1.264	0.807	63.8	36.2

a. Energy assumed directly proportional to areas under curves, figures 7 to 9.

The response of any given solar cell being subjected to insolation will not necessarily match the response of another solar cell being subjected to the same insolation. Therefore, the high albedos may be assumed to result from a greater amperage output of the bottom rack of solar cells as compared to the top rack when subjected to the same incident solar radiation. The instrumentation was not devised with the purpose in mind of measuring actual visible light albedos, but was based instead on measuring the relative visible light albedos of each of the rock types. Since the same instrument was used over each of the rock types, the calculated albedos would represent a measurement of the relative albedos of these rock types when compared to each other.

Since the albedo represents the per cent of energy reflected from a surface, the quantity $(1-\alpha)$ would represent the per cent of energy absorbed. Table 2 gives the calculated relative visible light albedos for each of the rock types measured. With regard to relative albedos, the results of the calculations are not unexpected. The Quaternary sands and gravels and the Pre-Cambrian granite present the lightest surfaces of the six rock types considered. The Pre-Cambrian schist is a dark green, and the andesite and basalt run from reddish black to black respectively. The calculations show that if each area is subjected to an equal quantity of energy, Quaternary sands and gravels and Pre-Cambrian granite will absorb less visible energy than the other four rock types.

Temperature Change Versus Time and Absorbed Insolation In Selected Rock Types

The incoming solar energy varied for each of the six days of measurements so that the temperatures recorded in each of the rock types (Figs. 10 to 12) cannot be considered to be a proper indication of the field conditions without considering the energy that produced them.

As stated, the diurnal variation of temperature in the ground is sinusoidal, with the maximum temperatures at the ground surface normally experienced in the early afternoon. As can be seen from figures 10 to 12, the maximum temperatures recorded at 1 inch occurred between 2:30 and 3:00 p.m. It was decided to divide the day into two periods - 8 a.m. to 3 p.m. and 3 p.m. to 8 p.m. From the field measurements, we have the change of temperature experienced by each rock type during these two time periods and a measure of the net energy contained within the visible portion of the energy spectrum which influenced this temperature change. Dividing the former by the latter, the figures shown in column 7, table 3 are calculated. These represent the temperature change which each rock type would experience if it absorbed the amount of visible energy as represented by one unit area measured by the solar cells. Column 7, table 3 shows that even though the rocks are still being subjected to visible energy after about 3 p.m., they experience a temperature decrease. This results from outgoing radiation $I_{\uparrow}$ and conduction $H_{\uparrow}$ exceeding all sources of incoming energy so that there is a net loss of energy at the ground.

The temperature measurements made in QTs, Qs, Ka, and p€s are considered an accurate representation of the temperature change for the time periods considered. The temperature measurements made in p€g for the time 0800-1500 are also considered to be accurate although measurements obtained for the time period 1500-2000 are poor for actually obtaining the temperature change for this time period. Instrumental difficulties in Qb rendered the temperature data poor for obtaining the temperature change for both the time periods under consideration. For the sake of comparison, however, a basic sine wave pattern will be assumed to obtain temperature change in both the basalt and granite.

As can be seen from column 7, table 3, the temperature change per unit visible energy received is larger for the rock type consisting chiefly of alluvial deposits. This would seem to indicate a possible decrease in the β-function of the alluvial deposits associated with erosion of particles in the hard-rock regions and their subsequent deposition in the lower areas. Normally, a density decrease would be expected in such a process, and it is generally felt that the thermal conductivity of the alluvial material is much lower than that in hard rock material although the specific heat of the alluvial material is considered to remain nearly constant. Chemical change of individual particles during the erosion-deposition process may become a significant factor in the final magnitude of the β-function also.

Table 3.--Rock Temperature Change Per Unit Net Energy of Visible Light During Periods of Rising and of Falling Temperature in Selected Rock Types, Harquahala Plains Area, Arizona

Rock type	Time period	Energy in[a]	Energy out[a]	Net energy	ΔT (°C)	ΔT / unit energy
QTs	0800-1500	0.856	0.607	0.249	19.5	78.3
Qs		0.798	0.582	0.216	26.0	120.4
p€s		0.877	0.529	0.348	14.5	41.7
p€g		0.849	0.603	0.246	21.5	87.4
Qb		0.988	0.585	0.388	22.0	56.7
Ka		0.880	0.537	0.343	22.5	65.6
QTs	1500-2000	0.314	0.209	0.105	-12.5	-119.0
Qs		0.337	0.256	0.081	-12.5	-154.3
p€s		0.343	0.233	0.110	-11.0	-100.0
p€g		0.236	0.192	0.066	- 8.5	-128.8
Qb		0.304	0.224	0.096	-13.0	-135.4
Ka		0.349	0.238	0.111	-10.5	- 94.6

a. Energy assumed directly proportional to area under curves (Figs. 7 to 9).

The major weakness in computing temperature change versus absorbed visible energy is that the effect that absorption of infrared energy had upon the temperature change versus time in each rock type is neglected. Also, it is not known whether or not longwave energy varied relative to visible energy from day to day. Thus, a rock type may be subjected to a certain amount of visible energy with a corresponding amount of infrared on one day and undergo a given temperature change as a result of absorption of this energy. On another day, it may be subjected to the same amount of visible energy, but a different amount of infrared due to increased or decreased absorption in the atmosphere. Thus, the temperature change could very well be different on this day as a result in the changed amount of infrared energy absorbed. However, it may be pointed out in favor of the computations that atmospheric conditions did not change significantly during the period of measurement as far as cloud cover or water vapor content is concerned. As a result, it can reasonably be assumed that the percentage of infrared to visible energy received did not appreciably change during the period of measurement.

The only sure method in which the relationships of visible energy to temperature change in rock type could be examined would be to measure these two quantities for a time period sufficient to establish the actual correspondence or to measure the entire spectrum of energy received from insolation, thereby knowing the quantity of infrared energy received.

From the preceding data, it can be definitely concluded, however, that the visible energy absorbed by the ground in the Harquahala Plains area will vary with rock type, and it can be inferred that this unequal absorption of visible energy will result in unequal temperature changes experienced by these rock types.

It is the unequal temperature changes which become important from the standpoint of the radiative properties of the various rock types. From equation 5, it can be seen that a difference of only several degrees between rock types can produce significant differences between rates at which energy is radiated into the atmosphere.

Calculated $I_{\uparrow}$

From table 2, it is seen that incoming solar radiation varied on each of the six days of measurement. This variance is probably a combination of instrumentation error or tolerance and actual variance in solar radiation received from day to day. In order to arrive at a better basis for comparison of the six rock types, it seems necessary to follow their temperature change with time as a result of being subjected to the same rate of insolation. An average value of insolation reaching the ground surface will, therefore, be assumed, and temperature changes will be computed on the basis of field data.

If the three variables of total incident insolation, back radiation, and temperature change at the ground surface are considered, it should be possible to arrive at some means for computing the magnitude of outgoing radiation of the various rock types for any day. It can be seen that the total incident insolation is independent of the other two factors, whereas back radiation and temperature change at the ground surface are both a function of the total insolation, the ground-surface albedo, and the thermal properties of the ground itself.

The relative albedos for visible light have previously been calculated for the selected surface rock types in the Harquahala Plains area, as well as the temperature change which each rock type will undergo if the energy absorbed by the rock is known. It should be possible then, by assuming an average value of incident insolation for this time of year, to rather closely approximate the temperature change that each of the various rock types under consideration would experience.

Sellers (written communication, 1964) shows that on the average, the ground surface in this area will experience between 650 and 700 ly/day. For the sake of calculation, it is assumed that some 660 ly are reaching the ground surface per day. Further, since those wave lengths below 0.29μ are terminated through ozone absorption, we will assume that approximately 50 per cent of the incoming solar radiation is composed of the visible portion of the spectrum and some 50 per cent is contained within the infrared. If the total units of area measured for the visible portion of incoming solar radiation over andesite are set to equal 330 ly, we obtain the result that each unit of area is equal to 261 ly. During the time period 8 a.m. to 3 p.m., andesite experienced 230 ly of visible energy, and from 3 p.m. to 8 p.m. it received 91 ly. These values will be assumed to occur over all the rock types. From equation 6, back radiation is equal to the albedo times incident insolation. By subtracting the albedo times incident insolation from the total insolation for the two time periods, we arrive at a value for net energy available to each rock type for absorption. Corresponding temperature changes are then calculated, and the average outgoing radiation $I_{\uparrow}$ can then be found from the relationship expressed in equation 5.

$I_{\uparrow}$ represents the energy which is available to the overlying air for absorption since it is longwave energy and thus, these values would determine the areas for the ordered preference of convective overturn if they exist.

The results obtained (tables 4 and 5) show that during the morning hours into mid-afternoon, there exists definite anomalies which are increased in the mid-afternoon. The data show that convective overturn as a result of radiation from the ground surface would be more likely to occur over the rock types in the following order: Qs > Ka > p€g > QTs > Qb > p€s for the time period 0800-1500 with the position of Qb being questionable. From 1500-2000, the data show the following order of rock types with regard to convective overturn: Qs > p€g > Ka > QTs and Qb > p€s with the position of Qb and p€g being questionable.

Table 4.--Calculated $I_{\uparrow}$ from Selected Rock Types from 0800-1500 Assuming Average Insolation Value for July, Over Harquahala Plains Area, Arizona

Rock type	Energy in (ly)	Energy out (ly)	Net energy (ly)	ΔT (^{o}C)	Initial temp (^{o}C)	Final temp (^{o}C)	Average temp (^{o}C)	σT^4 g-cal/cm^2 min
QTs	230.0	163.0	67.0	20.8	35	55.8	45.5	0.850
Qs	230.0	168.0	62.0	28.6	35	63.6	50.0	0.899
p€s	230.0	139.0	91.0	14.5	35	49.5	42.5	0.818
p€g	230.0	163.0	67.0	22.3	35	57.3	46.0	0.855
Qb	230.0	136.0	94.0	20.4	35	55.4	45.0	0.845
Ka	230.0	140.0	90.0	22.5	35	57.5	46.5	0.861

Table 5.--Calculated $I_{\uparrow}$ from Selected Rock Types from 1500-2000 Assuming Average Insolation Value for July, Over Harquahala Plains Area, Arizona

Rock type	Energy in (ly)	Energy out (ly)	Net energy (ly)	ΔT (^{o}C)	Initial temp (^{o}C)	Final temp (^{o}C)	Average temp (^{o}C)	σT^4 g-cal/cm^2 min
QTs	91.0	60.5	30.5	-14.0	55.8	42.0	49.0	0.888
Qs	91.0	69.0	22.0	-13.0	63.6	50.6	57.0	0.980
p€s	91.0	62.0	29.0	-11.0	49.5	38.5	44.0	0.834
p€g	91.0	74.0	17.0	- 8.5	57.3	48.8	53.0	0.933
Qb	91.0	67.0	24.0	-12.4	55.4	43.0	49.0	0.888
Ka	91.0	62.0	29.0	-10.5	57.5	47.0	52.5	0.927

RADAR OBSERVATIONS

The previous measurements are the result of field work during August and the first several days of September, 1964. During July through September, 1962, a radar installation under the supervision of Mr. H. E. Skibitzke of the Phoenix Research Section, Water Resources Division of the U.S. Geological Survey was set up and maintained in the Harquahala Plains. Figure 13 represents the final results obtained from the recordings of the radar for this time period. The intensities of the rainfalls observed were not established, but storms were mapped instead as to their location and duration. The results are shown in the manner of a contour map with contour intervals representing time of rainfall in minutes rather than elevation in feet.

There are two conflicting considerations in the use of radar for the observation of rainfall. When a wave passes over a raindrop, the water absorbs some of the wave energy, heating up a slight amount, while the rest of the energy is immediately re-radiated by the drop. This energy is re-radiated in all directions, but the amounts radiated outward from the radar set and back toward the radar set exceed the amounts radiated in a direction perpendicular to the beam. The behavior of the drop in radiating the intercepted power is referred to as "scattering." The power that is scattered directly back toward the radar is called "back-scattered" power, and it is this power alone that can be considered to be reflected back by the drop.

According to the Rayleigh scattering law, if the radar wave length remains fixed, the back scattering power of the raindrop is proportional to the sixth power of the drop's diameter. However, Rayleigh's law also states that back scattering is also inversely proportional to the fourth power of the wave length. Therefore, if the drop diameter were fixed, the back-scattered power would be considerably higher if a short wave length were used.

There is one other factor that must be taken into consideration. Those clouds and raindrops in between the raindrop and radar receiver will have a tendency to weaken the outgoing and reflected wave. This action is known as "attenuation." It has been found that the shorter the wave length, the stronger the attenuation (Battan, 1962).

A happy medium must be established then, in the selection of the type of radar to be used in the observation of rainfall. The radar used operated on a frequency of about 3,000 megacycles and was set at an angle so that it swept just barely over the ground. Thus, only the storms intense enough to cause rain to reach the ground were observed (Skibitzke, 1963). The wave length of the radar used was too large to make the observation of light rainfall (small raindrops) possible, and only those storms of rather high intensity and presumably larger raindrops could be monitored. This is not considered to be any great handicap to the final radar compilations as represented in figure 13, however, as most of the rainfall during the period of measurement can probably be considered as intense, so that there should be a rather close correlation between overall time distribution and rainfall amounts. The high time concentration in figure 13 should probably be greater than that shown since precipitation occurring during the waning moments of thunderstorm activity would probably not have been recorded, since raindrop size from a thunderstorm could be expected to diminish during this period.

The results of the radar measurements as shown by overlaying figure 13 on a geologic map of the Harquahala Plains area, figure 14, show the following characteristics for the distribution of rainfall, R, over the Harquahala Plains. First, the maximum time concentration (110 minutes $< R <$ 120 minutes) for rainfall was recorded in T. 2 N., R. 7 W., over Quaternary sands and gravels. The material slopes very gradually, approximately 50 feet/mile to the northwest, suggesting the Big Horn Mountains as the chief source area for the deposit. If this is the case, one would expect the sands and gravels to be mainly andesitic in composition.

The area over which the second highest time concentration of rainfall occurred (90 minutes $< R <$ 100 minutes) was over Quaternary sands and gravels located in T. 3 N., R. 9 W. and T. 3 N., R. 10 W. Here the land slopes approximately 100 feet/mile to the north, suggesting the northwestern portion of the Big Horns as the source area. Major rock types within this area of the Big Horn are basalt, andesite, and granitic gneiss. The Quaternary deposits in the area under consideration then, are probably some assorted mixture of these three major rock types.

Areas for which the time concentration of rainfall was greater than 70 but less than 80 minutes consisted of the Quaternary-Tertiary deposits in T. 5 N., R. 8 W. and T. 5 N., R. 9 W.; the Cretaceous andesite rocks located in T. 2 N., R. 11 W.; and the Quaternary-Tertiary sands, gravels and conglomerates and Cretaceous andesite located in T. 5 N., R. 7 W.

Areas of rainfall less than 70 but greater than 60 minutes, consisted of the Pre-Cambrian granite, Quaternary-Tertiary deposits in T. 5 N., R. 8 W. and the Cretaceous andesite in T. 4 N., R. 7 W.

The Quaternary basalt deposits in T. 1 N., R. 11 W. and Quaternary-Tertiary deposits in T. 2 N., R. 9 W. both experience rainfall concentrations of less than 60 but greater than 50 minutes.

At this point, it would seem wise to point out those factors that might have an affect on the recorded distribution of rainfall other than rock type. One of these factors would be the direction and speed of the winds aloft in the Harquahala Plains area during condensation and subsequent falling of raindrops. The average velocity of winds aloft in the area at this time of the year would be approximately 10 miles per hour in a northerly direction. For a thunderstorm, there will be approximately 20 minutes time lag between the beginning formation of raindrops and the subsequent falling of these drops as precipitation. During this time period, the winds aloft would probably push the clouds along with them so that actual rainfall could occur about 3 miles away from the point of conception.

Another consideration would be that of "terrain effect." Terrain effect refers to the effect which increased elevation has on precipitation distribution as it (1) presents a high heat source relative to lower altitudes, and (2) causes the air to move upward in order to cross them.

Both of these effects should result in increased rainfall. There appears to be no easy method for normalizing the effects of the high heat source, but the altitude effect is treated later.

The atmosphere itself must be considered as another factor in the final distribution of rainfall. It is the surrounding air that forces the heated air to move upward, and the atmosphere cannot be considered to be homogeneous in space and time. As a result, its ability to aid in the mechanism of convection would vary in a like manner.

In considering the effect of rock type on convectional precipitation distribution in a quantitative sense, it should be remembered that the total minutes of rainfall represents a quantity; and accordingly, one would expect that as the per cent of area to total area for a given rock increases, other things being equal, the total minutes of rainfall experienced by the area would increase.

Due to the effect of height upon precipitation as previously mentioned, one would expect total minutes of rainfall to increase with increasing height. Thus, the average total minutes of rainfall experienced by each rock type will have to be calculated, and this quantity corrected for altitude effect. Finally, the quantity of precipitation per unit area of rock type should be calculated, and this is the quantity that should relate to the outgoing radiation $I_{\uparrow}$, if a relationship between rock type and convectional precipitation distribution does exist.

The isohyetal method for averaging the areal depth of rainfall was used to compute the average total minutes of rainfall occurring over each area. The results are shown in table 6. It was decided to compute the average altitude of each rock type by arithmetic mean. These results are shown in table 6 also.

To compute the effect that a change in altitude would cause upon rainfall totals, the precipitation records of six towns that surround the Harquahala Plains area and for which adequate rainfall records were available were obtained (Sellers, 1960). The mean total precipitation that each station experienced from July through September was computed along with the per cent increase in precipitation with elevation experienced from station to station. Percentage increase of precipitation versus elevation increase is plotted in figure 15. The statistical method of least squares was used to plot the straight line relationship shown. This relationship is then used to correct the precipitation totals obtained from the radar. The corrected precipitation totals represent the total minutes of rainfall that each rock type would have experienced if it were at the same average altitude as the Quaternary sands and gravel deposits.

Finally, by dividing the value of corrected total minutes of rainfall by the respective areas, the rainfall per unit area is calculated over each rock type (see table 6).

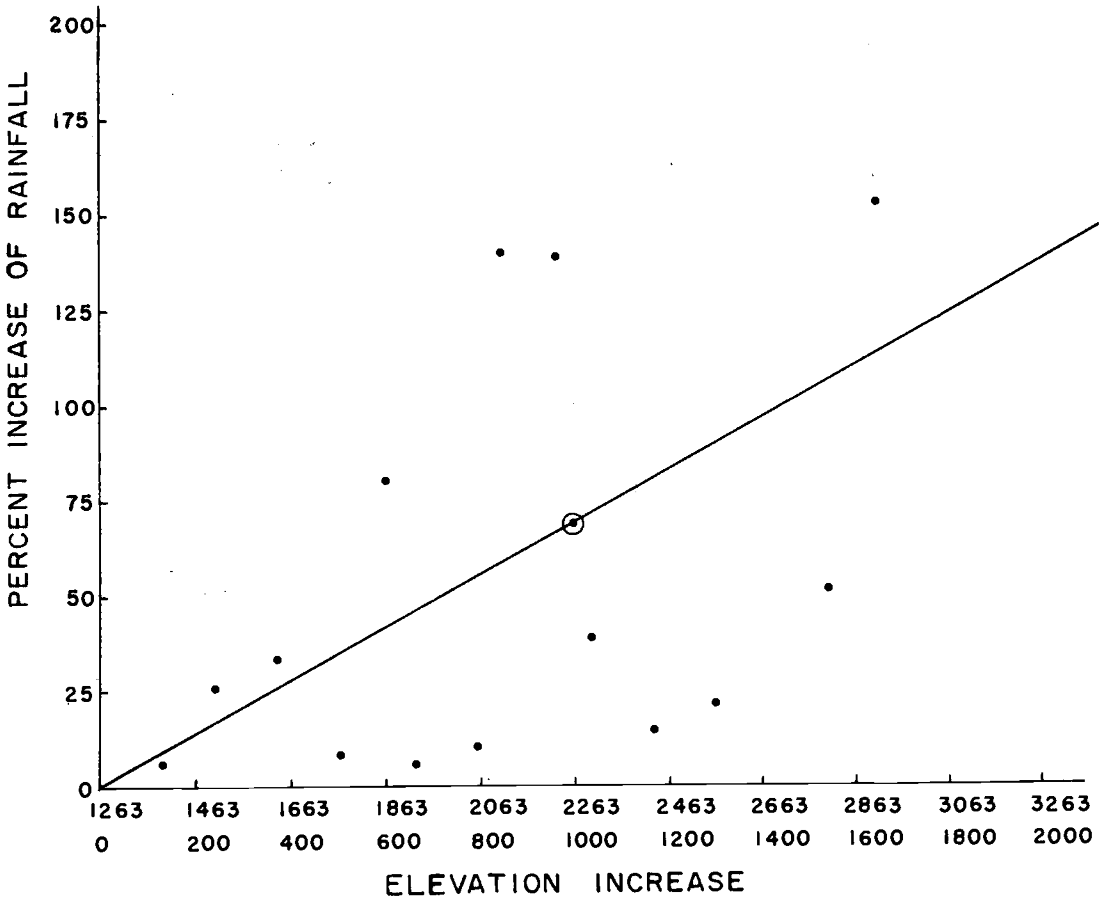

Figure 15.--Computed Per Cent Increase of Rainfall Versus Altitude for Southwestern Arizona

Table 6.--Calculated Total Minutes of Rainfall Per Unit Area Experienced by Selected Rock Types in Harquahala Plains Area, Arizona, for 1962 Summer Rainy Season After the Effect of Altitude Compensated For

Rock type	Area mi^2	Relative area	Total rainfall received (min)	Altitude correction			Corrected total rainfall received (min)	Total rainfall per unit relative area
				Elev (feet)	Rainfall increase (per cent)	Rainfall increase (min)		
QTs	459	4.387	25.0	1860	42.5	10.6	14.4	3.3
Qs	461	4.404	24.3	1263	0.0	0.0	24.3	4.4
p€s	20	0.187	29.9	1996	51.5	15.4	14.5	78.5
p€g	25	0.238	13.2	2153	62.5	8.3	4.9	20.6
Qb	80	0.762	28.1	1897	44.0	12.7	15.4	20.2
Ka	193	1.843	27.9	2350	76.5	21.4	6.5	3.6

CONCLUSIONS

The field data show the relative magnitudes of visible energy absorbed by the various rock types constituting the major exposed rock types in the Harquahala Plains area and show the temperature change which this energy helps to produce in each of these rock types. The magnitude of absorbed insolation and the temperature changes this energy produces are unequal as a result of intrinsic thermal properties of each of the different rock types, thereby causing differences in the rates of longwave radiation from each rock type into the atmosphere.

In comparing the calculated outgoing radiation values to the total minutes of rainfall/unit area as expressed in column 9 of table 6, the following relationships between convectional rainfall and exposed rock types appear to be evident. First, for those rock types composing a significant portion of the entire area considered, there appears to be a relationship between rainfall and radiation in that the greater the magnitude of outgoing radiation, $I_{\uparrow}$, the greater the rainfall experienced per unit area of the rock type. Second, for those rock types which comprise only a small percentage of the total area, there appears to be no definite relationship. It seems probable for this latter class of rock type that the rainfall they experience is in a large part controlled by their location relative to other rock types and by their altitude.

Not only rock type, but the percentage area of the rock type to total area appears to become an important factor in explaining the distribution of convectional rainfall. If the rock type is highly scattered in its distribution throughout the area considered, such as in the case of basalt in the Harquahala Plains area so that no one unit of the rock type comprises a significant portion of the area, it is possible that even the per cent area to total area will not be a good criteria for helping to determine the distribution of convectional rainfall. Just what percentage area to total area for a given rock type is necessary for correlation between exposed rock types and distribution of convectional rainfall is not known.

The high rainfall concentration over the Quaternary sands and gravels as compared to Cretaceous andesite suggests that erosion and deposition may become an important factor in final rainfall distribution in desert watersheds. If as has been suggested that the source material for the Qs deposits in T. 2 N., R. 7 W. is mainly the Cretaceous andesite, there would probably be little or no alteration of the individual grains from their previous characteristics subsequent to being eroded and deposited. Thus, each small particle of rock would maintain its previous characteristics. On a large-scale basis, however, the effect of erosion and deposition would be to decrease the density and conductivity in the new deposit as compared to the old, thereby decreasing the β-function of the new deposit. This then, allows the temperature change per unit time per unit quantity of energy received to be greater in the alluvial deposits as compared to adjacent hard rock areas.

The calculated temperature changes per unit visible energy absorbed by each rock type assumes that the proportion of infrared energy to visible did not vary from rock type to rock type and that proportional quantities of infrared energy were absorbed by each rock type. This latter consideration should not be a serious handicap to the final results as the infrared albedo of the various rock types can be expected to be nearly identical with each other.

With regard to the observed distribution of rainfall, some of the more evident factors that could have exerted a control on this distribution other than exposed rock have been mentioned. These included the time and space lag between raindrop condensation and subsequent falling as a result of the pushing effect of winds aloft on the drops; the terrain effect, which refers to areas of high elevations offering a high heat source; and the well known altitude effect on rainfall; and the inhomogeneous nature of the atmosphere itself over the Plains area, which is subjected to the radiation and is an integral part of the mechanism of convective overturn.

Finally, the fact that the relationship between rock type and rainfall distribution which is apparently evident from the field data might simply be the result of pure chance in that the rainfall distribution was not observed for more than one rainy season and the rainfall distribution for another rainy season may not be similar.

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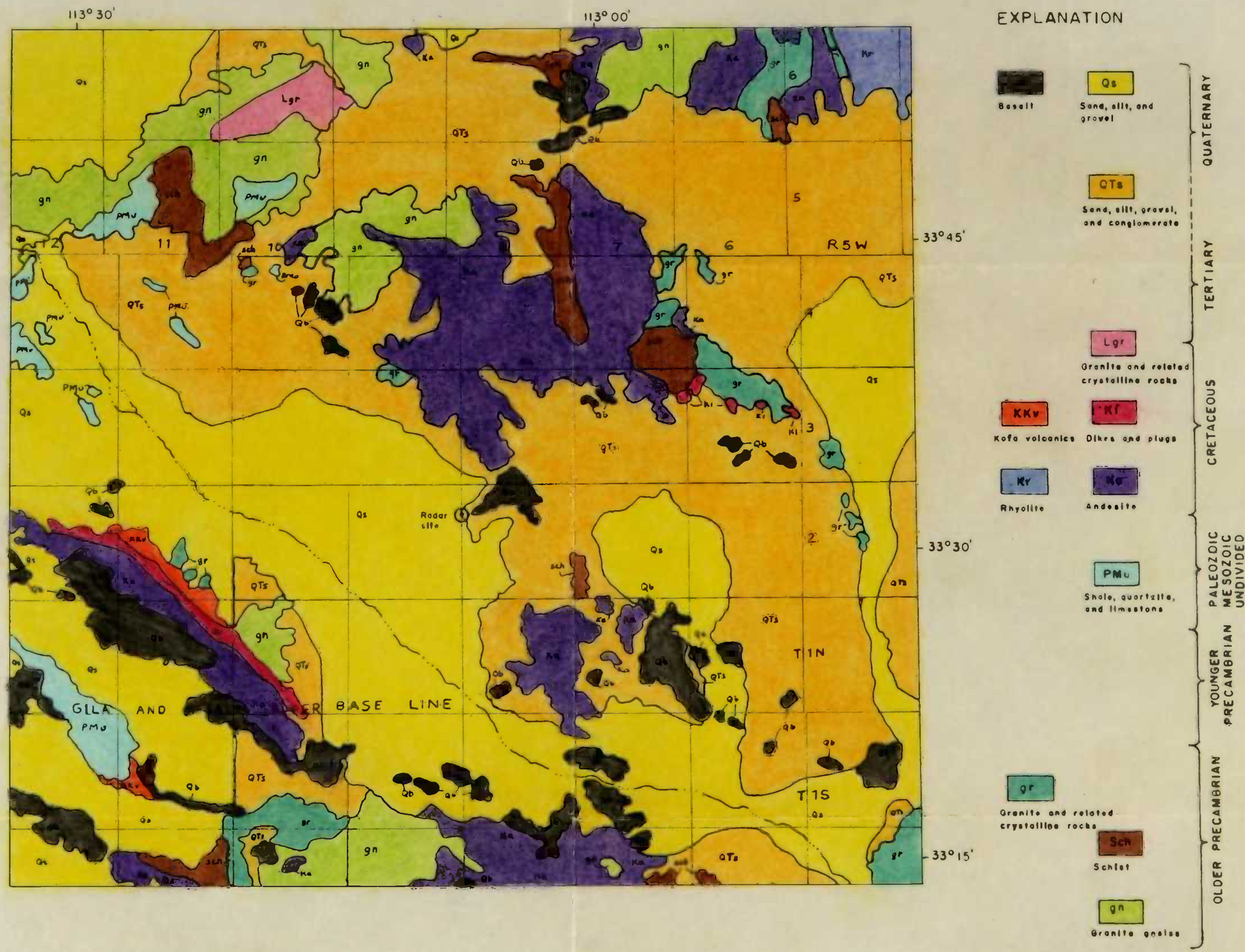

Figure 14 Geologic map showing Harquahala Plains Area, Arizona

(After Wilson and Moore)

Scale $\frac{1}{375,000}$

5 0 5 15 MILES

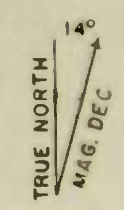

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Figure 13 The areal and time distribution of rainfall for the 1962 summer rainy season, Harquahala Plains Area, Arizona

0 10 20 MILES

Scale $\frac{1}{375,000}$

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