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Thermal/IR in Geology

Some limitations in the interpretation of imagery.

ABSTRACT: *It is easy to separate areas with different radiant temperatures, but it is very difficult to make definite statements about the properties of the surface materials using only their temperatures or temperature variations. Meteorological conditions mainly determine the actual radiant temperature, whereas the thermal properties of soil and rocks cause only minor variations. Increasing porosity causes lower thermal inertia and lower damping depths, resulting in higher temperature variations at the surface. Increasing water content generally augments the thermal inertia and the damping depths, and is responsible for smaller temperature variations. The mineralogy is only important in water-saturated soils and rocks or consolidated rocks with a low porosity. Therefore it is not possible to determine one parameter, e.g., water content, without the knowledge of at least a few others, e.g., porosity and weather.*

INTRODUCTION

THE CAPABILITY of recording variations in infrared radiation has tremendous potential application in extending man's observation of many types of phenomena in which minor temperature variations could be extremely significant or valuable in understanding our environment. Before any real progress in the application of this technique to mapping problems is possible, it is necessary to understand some of the basic physical principles involved. This is especially true in attempting to use this technique for determining rock or soil types for geological investigations.

HEAT BALANCE

The surface temperature of the earth is due to the heat balance represented by the following equation:

$$R_n + LE + H + G = 0$$

where R_n is the radiation balance, that is, the radiation irradiated by the sun and the sky onto the earth, minus the radiation which is reflected or emitted by the earth itself. LE is the latent heat, which is used for the transpiration of water by plants or the evaporation from the soils or is gained by the formation of dew. The term H describes the heat exchange between the surface of the earth and the air above the surface. G is the influent heat flux, i.e., entering the ground, or the effluent heat flux, i.e., migrating upward to the surface. During the day R_n is the most important term in the equation and the energy source of all the other processes. Most of the heat gain is used for evapotranspiration and the heating of the air. Only a small part (about 10 to 30 percent) heats the ground. During the night all energy fluxes are smaller, but now the effluent heat flux is very important and is the major source for the radiation of the earth in the thermal-IR.

With the present state of the art in remote sensing it is only possible to determine the radiation balance using the multispectral scanner. The determination of LE and H is difficult, even with ground measurements of meteorological parameters, e.g., temperature gradient and wind velocity. These determinations are only valid for areas where meteorological data have been collected and even then can vary significantly in any given area. Good results are obtainable only if (1) LE and H are small compared to G, or (2) it is possible to establish a relationship between LE, H, and G, which is valid for the

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TABLE 1. THERMAL PROPERTIES OF SOIL COMPONENTS

	Volume heat capacity C cal/cm³ °C	Thermal conductivity λ 10^{-3} cal/cm sec °C	Thermal diffusivity K 10^{-3} cm²/sec
Quartz	0.46	20	43
Clay minerals (mean)	0.46	7	15
Organic matter (mean)	0.60	0.6	1
Water	1.0	1.42	1.42
Air	0.000 29	0.062	0.21
Ice	0.45	5.2	11.5

meteorological conditions during the collection of the remote sensing data, or (3) *LE* itself provides useful information such as the detection of ground water saturated horizons at depth.

THERMAL PROPERTIES OF ROCKS AND SOILS

The surface temperature is influenced by both the influent or effluent heat fluxes and the thermal properties of the ground, which are determined by the percentage of the different components, including air and water. Table 1 (van Wijk and de Vries 1963, de Vries 1963) shows the thermal properties of the main constituents of the soil. The amounts of these constituents in the following sections are expressed as volume percentages.

VOLUME HEAT CAPACITY C

The volume heat capacity of soils and rocks is determined by the weighted mean of the volume heat capacity of their constituents.

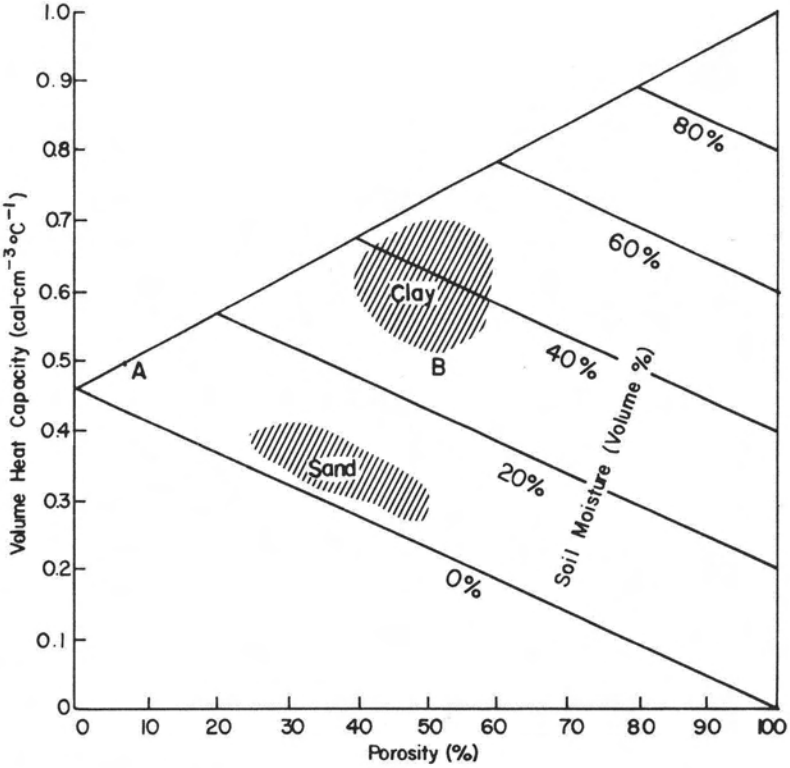

FIG. 1. Volume heat capacity *C* of soils and rocks with different porosities and moisture contents (calculated for average thermal properties).

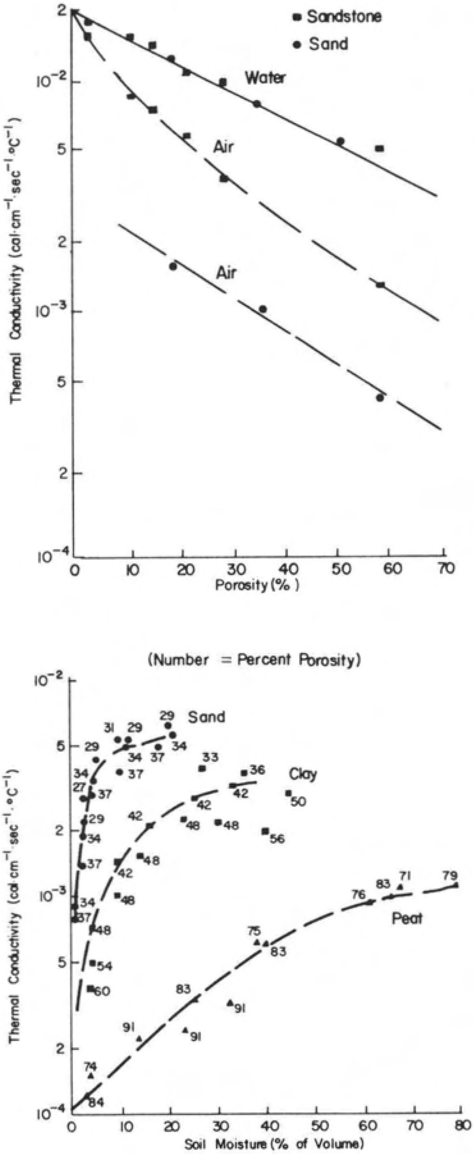

FIG. 2. Thermal conductivity λ. (a) (*Upper*) Variation with porosity, degree of cementation and water or air in the pores. (b) Variation with soil moisture for sand, clay and peat.

Figure 1 shows this relation for soils and rocks without organic matter and different porosities and moisture contents. One sees clearly, that a distinct heat capacity, e.g., 0.5 cal/cm^3 °C can be related to a variety of different rocks, such as water saturated sandstone with 8-percent porosity (Point *A*) or a clay with 50-percent porosity and 27-percent water (Point *B*).

THERMAL CONDUCTIVITY λ

The thermal conductivity λ is also related to the amount of the different constituents, but the relationships are more complex. Figure 2a (after Woodside and Messmer 1961 a, b) shows the thermal conductivity for sand and sandstone with water filled pores (upper curve), dry sandstone (middle curve) and dry sand (lower curve). The thermal conductivity decreases for all three media with increasing porosity. Whereas only a small difference exists between sand and sandstone if both are filled with water, the difference becomes significant if air is present instead of water.

The variation of the thermal conductivity with moisture content is not linear. Figure 2b shows this relation for three different soil materials: sand, clay and peat (de Vries, 1963). The increase of the conductivity is very high at low moisture contents (high *pF*) and becomes very small with higher moisture contents (low *pF*). For moisture contents between field capacity and wilting point the conductivity for both sand and clay is between 2 and 5×10^{-3} (cal/cm sec °C). For example, a variation in porosity between 48 and 33 percent produces a change in the thermal conductivity of clay in the same range as would be produced by a change in moisture content from 20 to 50 percent.

Figure 3 shows that only a small increase of the thermal conductivity of a sediment with 36 to 38 percent porosity occurs if the thermal conductivity of the minerals increases (Woodside and Messmer, 1961 a, b). For example, if the thermal conductivity of the minerals increases from 2.5 to 20×10^{-3} cal/cm sec °C, that is, by a factor of 8, the conductivity of a water-saturated rock in-

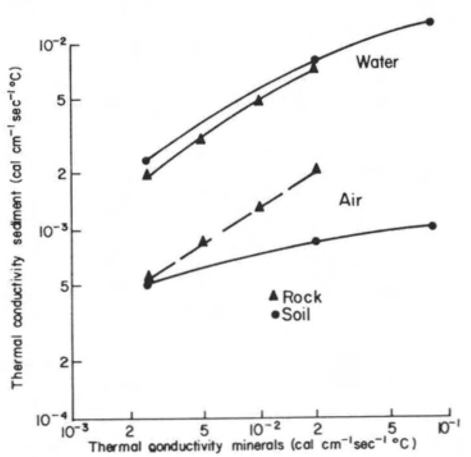

FIG. 3. Correlation between the thermal conductivity of minerals and the thermal conductivity of rocks and soil, containing these minerals.

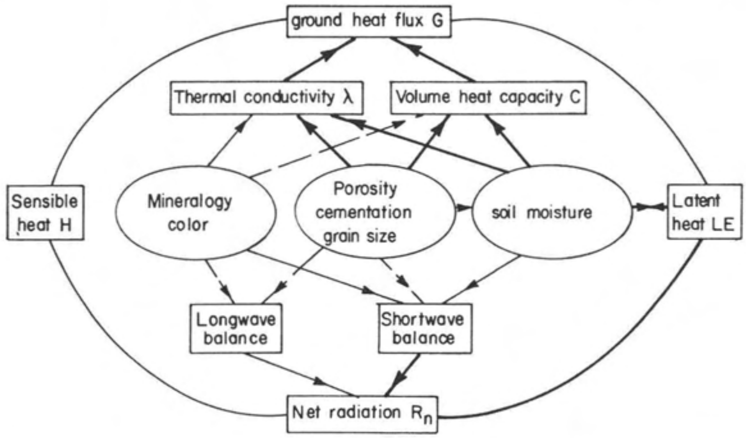

FIG. 4. Influence of geological parameters on the heat balance equation.

creases only from 2 to 7.4 (a factor of 3.7) and that of a dry soil from 0.5 to 0.85×10^{-3} cal/cm sec °C (a factor of 1.7). Thus, compared with the influence of porosity and water content, these variations are small, especially in dry, unconsolidated sediments.

The important characteristics of rock and soils, mineralogy, color, porosity, cementation and water content and their influence on thermal conductivity and volume heat capacity are shown in Figure 4. An examination of this figure shows that there is only a minor direct relationship between these parameters and the longwave radiation balance, part of which is measured with thermal IR sensors. Meteorological conditions, e.g., wind speed, temperature, cloud cover, are more important in the heat balance and determine the measured thermal radiation.

TEMPERATURE VARIATION AT THE SURFACE

In general it is possible to describe the surface temperature variation as a sinusoidal oscillation.

The surface temperature variation for two different soils is inversely proportional to the thermal inertia $\sqrt{\lambda C}$, if the heat flux is the same for both soils. Figure 5a (compare with Figure 2a) shows that the decrease of thermal inertia, hence increase in temperature amplitude is due to increasing porosity and is relatively low for water-saturated sand and sandstone, but high for both air filled sand and sandstone. Figure 5b shows that the thermal inertial increases directly with the water content. Figures 5a and 5b illustrate the following conclusions:

- Only for water-saturated rocks and soils or rocks with low porosity can any interpretation of mineralogy be made from thermal data. In all other instances the influence of porosity and moisture is far more important.
- Within one soil type the increase of the thermal inertia with increasing moisture is important at low water contents, resulting in greater temperature variation at the surface for dry soils.
- Peat can have a lower thermal inertia than clay and sand. Therefore it has, under certain conditions, a higher temperature at the surface during the day than either of the other materials. The conclusion that cold is wet and warm is dry is therefore not always valid.

The ratio of the temperature amplitude between different soils is smaller than the ratio of the thermal inertias. A higher surface temperature causes a higher heat exchange rate with the adjacent air and a higher IR emissivity and therefore lower heat flux into the earth during the day. If, for example, the ratio of the thermal inertial between two soils is 1.6, the ratio of the temperature amplitudes could be between 1.5 and 1.1, depending on the surface structure and meteorological conditions.

DAMPING DEPTH OF THE TEMPERATURE WAVE

The surface temperature depends not only on the thermal characteristics of the surface layer but, to a certain degree, also on the thermal behavior of the subsurface layers. The influence of the subsurface layers is negligible if the thickness of the surface layer is more than twice their damping depth, and becomes important only if the surface layer is not thicker than the damping depth (van Wijk and Derksen, 1963). The thermal diffusivity $K = \lambda / C$ and the period ω determine the damping depth

$$D = \sqrt{2K/\omega}.$$

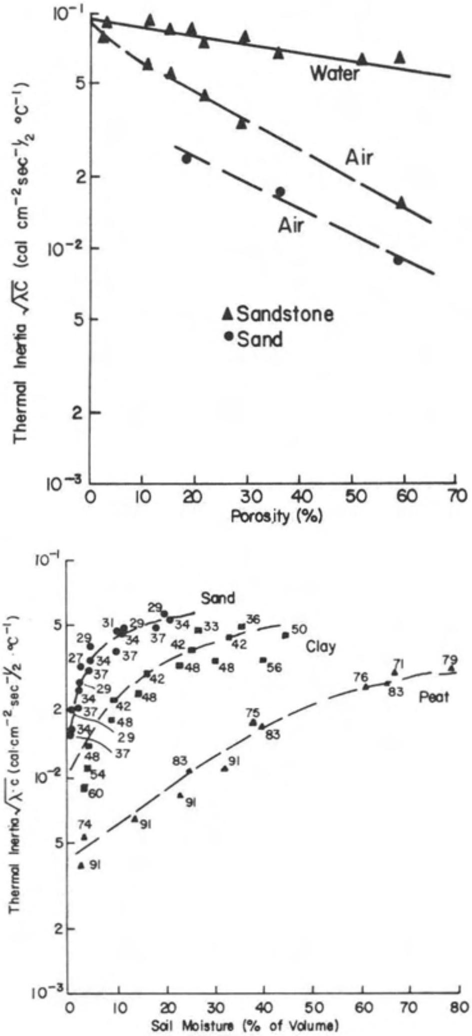

FIG. 5. Thermal inertia $\sqrt{\lambda C}$ (a) *(Upper)* Variation with porosity, degree of cementation, and water or air in the pores. (b) Variation with soil moisture for sand, clay and peat.

Figure 7 shows the thermal diffusivity and the damping depth for a diurnal oscillation. In most instances the damping depth is smaller than 15 to 20 cm and attains more than 30 cm only in consolidated rocks with low porosity. Thus, statements about the boundary between two layers or the characteristics of the subsurface layer, using the diurnal variation, are only possible if the surface layer is not thicker than 60 cm, in most instances not even thicker than 25 cm.

Example. Figure 6 shows the radiant temperature of a gravel with varying depth of the groundwater table as measured during a

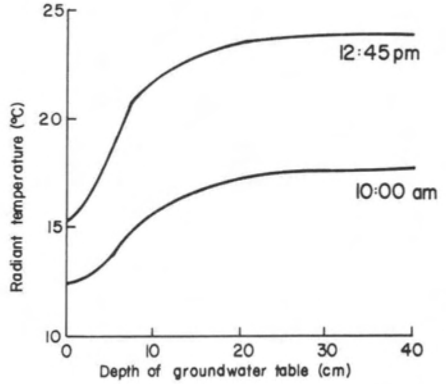

FIG. 6. Radiant temperature versus depth of groundwater table for gravel under clear sky at 10:00 a.m. and 12:45 p.m.

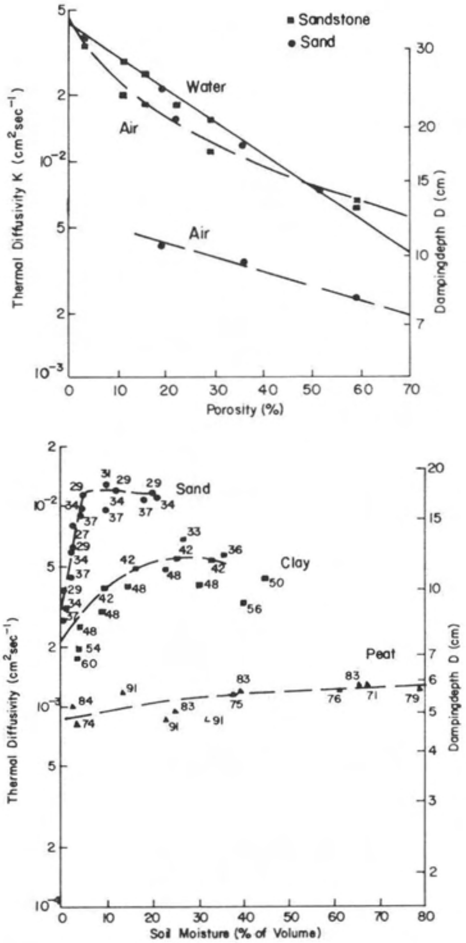

FIG. 7. Thermal diffusivity K and damping depth D of a diurnal oscillation. (a) (*Upper*). Variation with porosity, degree of cementation and water or air in the pores. (b) Variation with soil moisture for sand, clay and peat.

day with a clear sky, calm or low wind velocity, at 10:00 a.m. and 12:45 p.m. The radiant temperature of the dry gravel (groundwater table below 20 cm) is higher than the radiant temperature of the wet gravel (groundwater table 0 cm), due to the lower thermal inertia of dry gravel (see Figure 5b for sand). For the same reason, the surface temperature of the dry gravel augments between both times — twice as much as the wet gravel (6° C versus 3° C). This ratio is comparable with the expected results using Figure 5b. The greater evaporation of the wet gravel causes an additional decrease of the temperature augmentation for this type of surface material.

The influence of the groundwater is negligible if it is more than 20 cm below the surface, due to the low damping depth of the dry gravel (Figure 6b), which causes very small temperature variations in the subsurface layers.

ACKNOWLEDGMENT

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