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ON IR IMAGERY AND ITS APPLICATION TO THE MAPPING OF GEOTHERMAL DISTRIBUTIONS

K. MATSUNO, H. HASE AND K. NISHIMURA

Applied Geological Department, Geological Survey of Japan, Kawasakishi (Japan)

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SUMMARY

The writers introduce case histories of IR geologic study in Japan and mention some future aspects of further study. They also show several examples of IR images and give short comments on them from a geologic standpoint.

The IR images were obtained by means of InSb detectors. The images give the approximate thermal distribution of the earth surface investigated. Factors which influence the imagery are outlined, but not discussed in connection with the presented images.

INTRODUCTION

In 1964, the term "Infrared Geology" was first proposed by CANTRELL and in the same year FISCHER and MOXHAM (1964) made sure that the infrared imaging sensor could be adopted for the mapping of the geothermal distributions on the earth's surface. In Japan, this field of science has come into the limelight in connection with current geothermal resources explorations.

Infrared radiation is an electromagnetic radiation, the position of which in the electromagnetic spectrum lies between visible light and microwaves. For convenience the term "infrared" will be abbreviated to IR throughout this paper.

The term "IR imagery" discussed in this paper is quite different from the commonly used "IR photography" which is recorded with the near IR part of the spectrum on photographic sensitive emulsion by conventional cameras.

All natural objects emit IR radiation and the energy radiated by an object is proportional to the 4th power of its absolute temperature and proportional to its emissivity. The maximum radiant energy of an object at the atmospheric temperature of about 300° K is in the region of wavelength about 9–10 μ in the spectrum. To record the relative intensity and spatial configuration of the radiated energy from the surface of an object in the form of an image, IR sensors with scanning systems will be applied. IR radiation collected by optical systems which scan a total field of view with an instantaneous one, is focussed upon a photoelectric type of detector and transformed into an electric signal. The amplified electric signal is reconverted into visible light and recorded by scanning on a conventional photographic film in an image form, whose tonal density corresponds to the strength of radiant energy. Thus, the thermal distribution can be mapped.

It is believed that this type of instrument can be adopted to the mapping of the thermal distribution of the earth's surface for the purposes of geophysical and geological investigations and prospecting. At the present time, IR geology has just started and we have not enough knowledge to fully utilize the information provided by airborne IR sensors for geophysical and geological purposes. This can only be achieved by a combination of related laboratory studies and field geologic appraisal of images.

TECHNICAL DEVELOPMENT IN JAPAN

In 1964, the first IR imaging sensor named Infravision–I was produced by the Nippon Electric Co. resulting from research work which had been commenced in July, 1960. One of the authors, Matsuno, has been much interested in IR imagery which could record effectively the geothermal regime on the earth's surface at any time from the air in an image form, after hearing a lecture given at the U.N. Course for Aerial Survey in Tokyo, 1961, by Dr. W. A. Fischer of the U.S. Geological Survey.

The successful results of both the IR investigation of a Hawaiian volcano in the winter of 1963 by Fischer and Moxham (1964) and the IR radiometric survey of the Japan current by the Japan Maritime Safety Agency in the winter of 1964 have stimulated us to develop an IR imaging sensor for the purpose of reconnaissance of the earth's surface from the air.

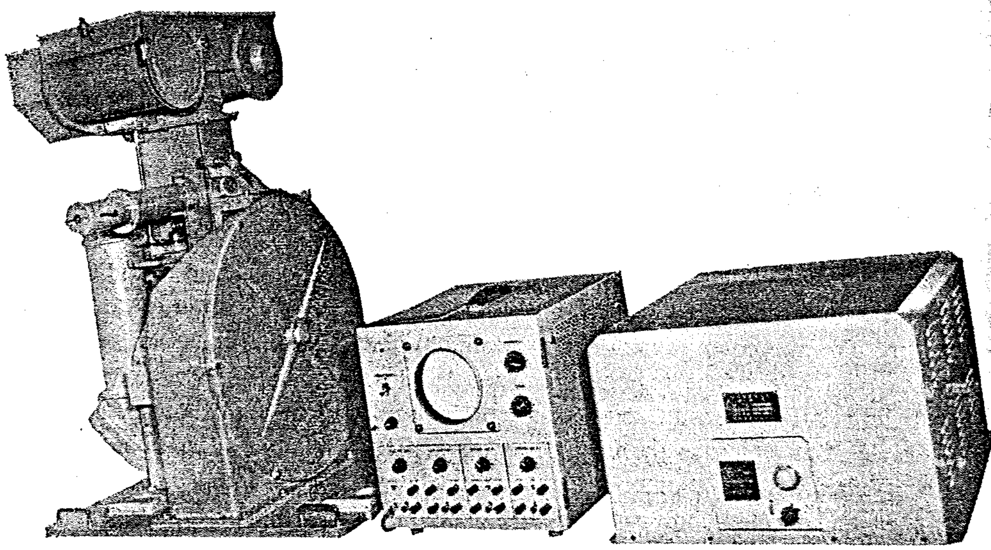


Fig.1. Infravision (IRV)–III, airborne infrared imaging sensor. (Courtesy of Nippon Electric Co,).

In the beginning of 1966, the Geological Survey of Japan conducted experimental studies on the mapping of geothermal distributions at the test sites in Sesshô-seki, of Nasu volcano, and Oowakudani, of Hakone volcano, using Infravision–I from the ground in cooperation with the Nippon Electric Co. These tests were successful in obtaining several images and valuable data which would contribute to the development of new IR imaging sensors. Particularily, it was noticed that an airborne system should be adopted for the geologic reconnaissance of a wide area.

Following the above mentioned experimental studies, production of Infravision–II, improving Infravision–I, and the first IR airborne sensor, was started immediately by the Nippon Electric Co. At the end of the year, an operation test of a new sensor Infravision–III (Fig.1) in the air, and necessary adjustments of it, were carried out by flying over the area from the southern portion of Tokyo to the Pacific coast. Here the first IR images from the air were obtained.

In February and March of 1967, the first experimental flights aimed at geothermal mapping in Japan were carried out by the Geological Survey of Japan, the Nippon Electric Co. and the Asia Air Survey Co., in the southern Kwanto district. These were quite successful in recording several thermal anomalies related to the volcanic activities and dispersal pattern of discharge water of the Katase river into the Pacific Ocean.

In the fiscal year of 1967, the subsidiary fund for the experimental research works on the mining and industrial technology was granted to the Nippon Electric Co. for the development of the airborne IR imaging sensor.

BASIC PHYSICAL LAWS AND PRINCIPLES RELATED TO IR RADIATION

IR radiation is an electromagnetic radiation. Any material whose temperature is above absolute zero generates IR radiation by vibration and rotation of atoms and molecules. The intensity of energy of the electromagnetic radiation depends largely upon the absolute temperature of the material, i.e., IR radiation generates heat in any absorbing object in its path since it causes vibration or rotation within the atomic structure of the object. Because of this phenomenon, IR rays are often called "heat waves". However, IR radiation, unlike a heat wave is not transferred by thermal convection or conduction on a physical medium, and this usage of the term is not correct. This kind of heat effect is also recognized in other forms of electromagnetic radiation such as the X-ray and radar beam, although they have no heat effect themselves.

The IR part of the spectrum extends over the wavelength region from 0.7 μ at the longest limit of visible light, to 1,000 μ at the shortest limit of microwaves. This region is subdivided into three parts; namely, near, middle and far IR (Fig. 2). IR radiation is reflected from, transmitted through and absorbed by, materials: the absorbed IR radiation causes a temperature increase of the materials. Thus, IR radiation has some of the characteristics of both visible light and radar or radio waves. It can be optically focussed and directed by lenses and mirrors, or dispersed by prisms. At the same time, it can be transmitted like radar or radio waves through materials which are opaque to visible light.

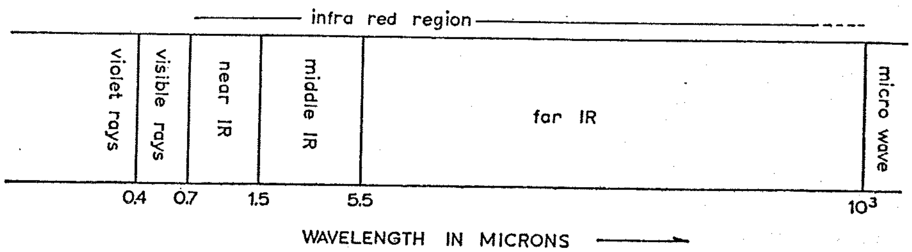


Fig.2. Position of infrared radiation in the electromagnetic spectrum.

The degree of absorption and radiation of an IR ray is dependent on the material. That is to say, the good absorbing material is the good rediating one, according to Kirchhoff's law. An idealized material which converts all absorbed energy to the radiating is called a black body. There are three principal physical laws related to IR radiation from a black body.

Planck's Law

The relationship between the radiation intensity, spectral distribution and temperature of a black body is given by PLANCK's law which states that:

$$W_\lambda = \frac{c_1}{\lambda 5}\left[\exp\left(\frac{c_2}{\lambda T}\right) - 1\right]^{-1} \tag{1}$$

where W_λ = spectral radiant emittance of the black body at wavelength λ and at temperature T: it is measured in watts/cm^2 per unit wavelength; T = absolute temperature of the black body, °K; λ = wavelength of emitted radiation; c_1, c_2 = constant, $c_1 = 5.95 \cdot 10^{-17}$ watt m^2, $c_2 = 1.43848$ cm deg.

Stefan-Bolzmann Law

Total radiant emittance into a hemisphere from a black body at an absolute temperature T is given by the equation:

$$W = \int_{\lambda=0}^{\lambda=\infty} W_\lambda \, d\lambda = \sigma T^4 \tag{2}$$

where W = total black body radiant emittance measured in watts/cm^2 of the radiating surface; σ = Stefan-Bolzmann constant = $5.673 \cdot 10^{-12}$ watt/cm^2 deg^4.

Since we have integrated over the whole wavelength region, W is not wavelength-dependent: dependent upon the 4th power of the absolute temperature of a black body.

Wien's displacement Law

The wavelength which gives a maximum radiant emittance is obtained when we differentiate W_λ with respect to λ and set the derivative equal to zero:

$$\lambda_{max} T = K$$

where K = constant = 2,897 $\mu \cdot$ deg

Actually, such an idealized material as a black body with an emissivity of 1.0 is not expected. All materials are gray bodies which radiate or absorb less than a black body at the same temperature. Then, the emissivity factor Σ must be considered always. It is defined as the ratio of total radiant emittance of a gray body to a black body at the same absolute temperature. Thus, the Stefan-Bolzmann law applied to a gray body becomes:

$$W = \Sigma \sigma T^4 \qquad (4)$$

A highly polished surface of silver plate is an extremely poor absorber and radiator and its emissivity is less than 0.1, close to zero. On the other hand, a platinum black body conducts nearly as well as a black body. Among natural objects, water surface is one of the most black body-like material and its emissivity exceeds 0.9. Grass covered rock and soil surfaces are valued 0.8–0.9 in emissivity.

Black body radiant emittance vs. wavelength is shown in Fig.3. As the temperature of a black body increases, its radiation peak shifts toward the shorter wavelength side. In the case of solar energy whose spectrum approximates that of a black body at temperature of 6,000°K, its peak radiation is at the wavelength of

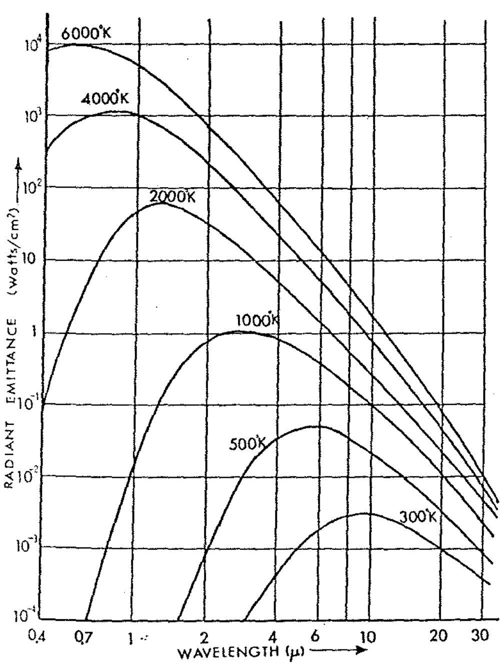


Fig.3. Blackbody radiant emittance against wavelength.

0.48 μ. If the temperature of the source is lowered to about 300°K, to approximately that of the atmosphere, the wavelength of its peak radiation shifts to 9–10 μ.

BASIC FACTORS RELATED TO THE INTERPRETATION OF IR IMAGES

Though the IR images can record effectively the relative intensity and spatial configuration of the thermal pattern of the earth's surface and contribute to solving many problems in the field of geology and geophysics, there are many factors related to the images provided by the sensor as well as many other problems yet to be solved. These include:

(*1*) the imaging sensor itself, and navigation for an imaging operation;

(*2*) attenuation of IR radiation in the atmosphere;

(*3*) problems related to endogenetic and exogenetic thermal energy.

Among many problems, it is felt that the above three are most important for analysis of the images, and all of them contain many additional problems.

(*1*) The imaging sensor must be designed to collect radiant IR energy focussed on to the detector with the least attenuation of radiant IR energy, by the optical system. There are many limitations and problems related to the optical system because the IR part of the spectrum has a broader range than that of the visible part of the spectrum. These are related to the materials used for optical systems, scanned spectral region, resolution, sensitivity and response speed of the detector used, and others. In addition to the above, the relation between the rotation speed of a scanning mirror of a sensor and the speed of the airplane used, in respect to the instantaneous field of view of the sensor, orientation of the airplane in night time operation, limitation of weight of the sensor and its accessories, and other technical problems, must be carefully considered.

(*2*) The IR energy emited or reflected from the earth's surface, travels through the earth's atmosphere and is attenuated in its path. Attenuating factors related to atmospheric transmission fall into three categories; namely: (*a*) resonance absorption of atmosphere; (*b*) scattering, mainly caused by water vapor, and (*c*) temperature, atmospheric pressure and others.

The periodic motions of electrons in the atoms of a source, vibrating and rotating at certain frequencies, cause the radiation of electromagnetic waves at those frequencies. The earth's atmospheric constituents contain bound charges or electrons with natural frequencies of vibration and rotation which depend upon the construction of the molecules. When these characteristic frequencies are matched by that of the incident radiation, resonance absorption occurs. Attenuation of IR radiation through the earth's atmosphere is mainly caused by resonance absorption of triatomic molecules such as water vapor (H_2O), carbon dioxide (CO_2) or ozone (0_3). By this resonance absorption, incident IR radiation is absorbed by atmospheric constituents and re-emission begins.

Fig.4 shows IR transmission and absorption bands of these primary constituents of the atmosphere out to a wavelength of roughly 16 μ. The wavelength

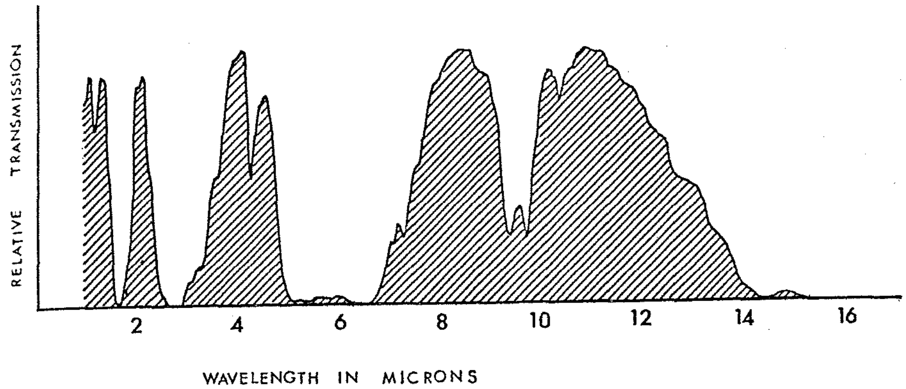


Fig 4. Infrared transmission (shaded area) and absorption (clear area) bands of primary atmospheric constituents out to a wavelength of 16 μ.

regions between absorption bands (clear areas) are called "infrared windows" (shaded areas), among which the 8–14 μ band is the most useful spectral region to obtain IR imagery of the earth's surface at near atmospheric temperature, from remote high altitude.

Water vapor is the principal attenuator of IR radiation in the earth's atmosphere, and its concentration and distribution in the atmosphere are changing continually. Consequently, accurate characteristics of absorption due to atmospheric water vapor can not be obtained. Elsasser gives a model describing the effects of spectral-band absorption through the wavelength at the lower altitude.

In the second, the absorption of IR radiation by carbon dioxide is important. However, the distribution of carbon dioxide in the earth's atmosphere is practically constant and virtually independent of weather conditions. The effect of ozone can be neglected for most purposes because all atmospheric ozone is limited to a layer at an altitude of approximately 20–30 km.

Another attenuation is caused by scattering which does not depend upon proper frequencies of molecular vibrations as in the case of attenuation by absorption. On the scattering phenomena, several laws have been proposed. Among them, Rayleigh's law is applied for scattering due to particles smaller in diameter than the wavelength of the incident radiation, namely molecular particles. For scattering due to larger particles such as haze or smog (particle diameter ranges from 0.1 to a few microns), cloud and raindrops (often over 100 μ in diameter), Mie's scattering theory is applied.

In low density fog, IR radiation has a better transmission in comparison with visible light. On the other hand, in rainfall, transmission of IR radiation is in the same condition as visible light. Even on fine days, dense haze or fog very often occurs in mountainous areas or in coastal regions. For an airborne IR imaging operation in these areas, much attention has to be paid.

(*3*) For geological or geophysical purposes, investigations of the thermal patterns recorded on the IR images must be conducted from the view point of heat budget of the earth's surface. That is to say, whether high of low anomalies are resulted from endogenetic energy or exogenetic one. Therefore, considerations of local minor or micro-climatological conditions are inevitable, and the influences due to topographic characteristics must be considered.

In Fig.5, the generalized heat budget on the terrain surface in the daytime and

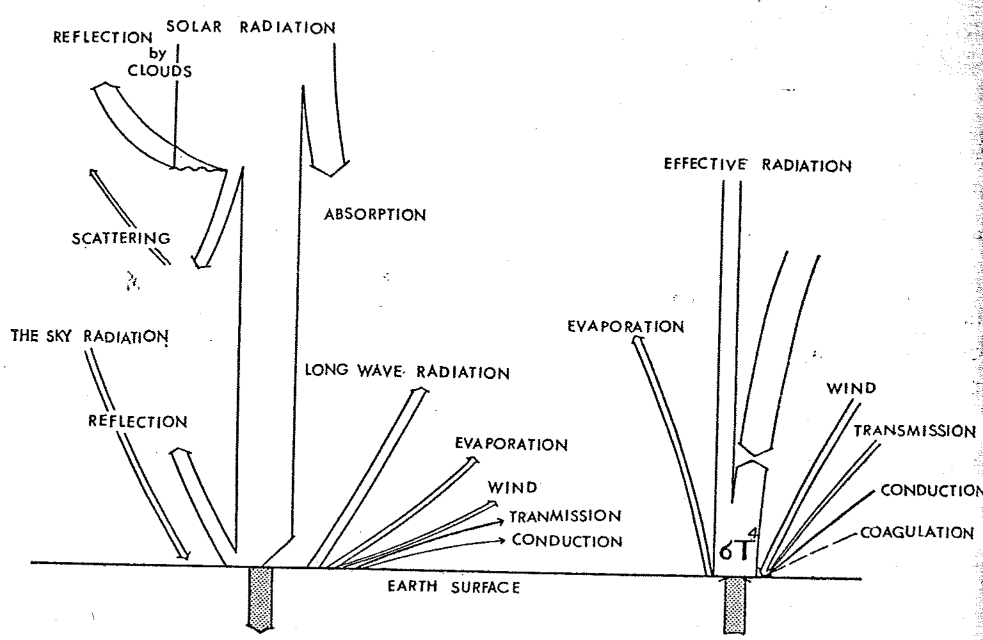


Fig.5. Heat budget in the daytime (on the left) and in the night time (on the right) on the earth's surface.

night time is shown. The primary effect which controls the temperature of the terrain surface is solar radiation. To survey or map the geothermal distribution due to endogenetic energy, exogenetic effects caused by the solar radiation should be avoided. For this reason, imaging operations must be carried on in the night time when the solar effect is at a minimum.

In connection with the effect caused by the solar radiation, a field temperature measurement was carried out by the writers at Yuba, Ooshima Island through the day. The temperature of the sunny side of the slope is a few degrees centigrade higher than that of the shaded one in the daytime. This condition continued until dawn the next morning (Fig.6). As a result, it is concluded that the effect caused by the solar radiation is a parameter dependent on the topographic features.

Inverse square law

In relation to the topographic altitude difference of the terrain surface, the inverse square law which states "the intensity of radiation emitted from a point

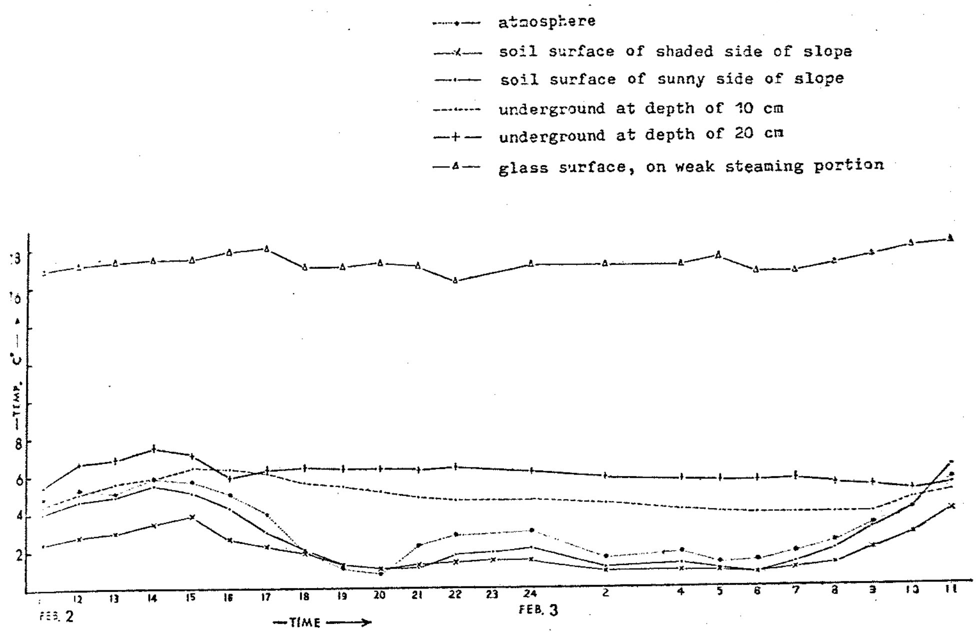


Fig.6. Temperature variations measured at Yuba, Ooshima Island.

source varies as the inverse-square of the distance between source and receiver" must be considered.

If the total energy radiated by a black body point source (S) into a hemisphere is W Watts/cm^2 of the radiating surface, the IR energy received by two detectors of equal sensitive area of 1 cm^2, D_1 at d cm and D_2 at $2d$ cm from S, are $W/2\pi(d)^2$ and $W/2\pi(2d)^2$ respectively (Fig.7). As a consequence of the above, the

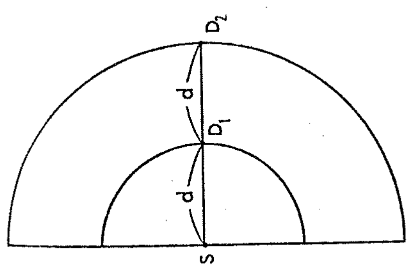


Fig.7. The inverse square law.

ratio between flying height of an airplane and the maximum altitude difference of the terrain surface of which geothermal distributions are observed, is quite an important factor.

Lambert's cosine Law

The radiant intensity emitted for all wavelength intervals varies as the cosine of the angle between the line of sight and the normal to the surface. In general, the above angle varies in respect to the position of the scanning mirror in rotation and the position of an airplane to the terrain surface on which geothermal distribution is observed from the air.

The temperature on the earth's surface depends primarily upon the effect of solar energy and changes continually through the day. For this reason, an isogeothermal counter map is compiled, based upon point to point measurements at the bottom of shallow drilling holes of 1–1.5 m depth to minimize the solar energy effect, in the conventional method.

IR imagery here discussed displays the thermal distribution of the earth's surface, on which the effect of the solar energy influence is, more or less, as already mentioned above. Therefore, in some cases, the thermal anomalies recorded on the IR imagery are quite different from the true geothermal anomalies. To obtain the true geothermal anomalies, much careful consideration should be taken up.

DESCRIPTION OF IR IMAGES

A detecting element sensitive to radiation in the 1.2–5.5 μ part of the spectrum was used to obtain the IR images described in this chapter. A resultant image whose tonal gradient is controlled by the instantaneous energy focussed upon the detector, represents the relative intensity and spatial configuration of the radiant energy of the observed area. Thus the tonal gradient of an image is a function of surface temperature and emissivity. As the emissivity of the earth's surface materials and vegetations ranges to some extent, the tonal gradient of an image shows "apparent surface temperature". Lighter tone on an image indicates higher surface temperature. As already mentioned, the result of the field temperature measurements at Yuba, Ooshima Island on February 2–3, 1967 confirmed that the thermal anomalies have a maximum contrast with their natural surroundings during the hours 20h00–06h00.

Ir imagery of an area in the Miharayama caldera

Fig.8 and Plate IA show the map of the Miharayama caldera and IR imagery of an area of the Miharayama caldera, from 1,000 m in altitude. Almost the whole of the area imaged is covered with lava flows, scoria and ash, formed in earlier ages, except for the inner wall of the caldera rim in which pyroclastic materials of pre-caldera age crop out and which are not covered with vegetation. Within the area, at least three thermal anomalies are recorded on the images. Through the field investigation of the anomaly on the inner wall of the caldera rim in April 24, 1967, it was found that there was a series of thermal anomalies whose temperatures were 4°–5°C higher than that of the surroundings. In conclusion, there would be a slightly higher temperature contrast at the time when the image was taken, if the change of average temperature from March to April is considered.

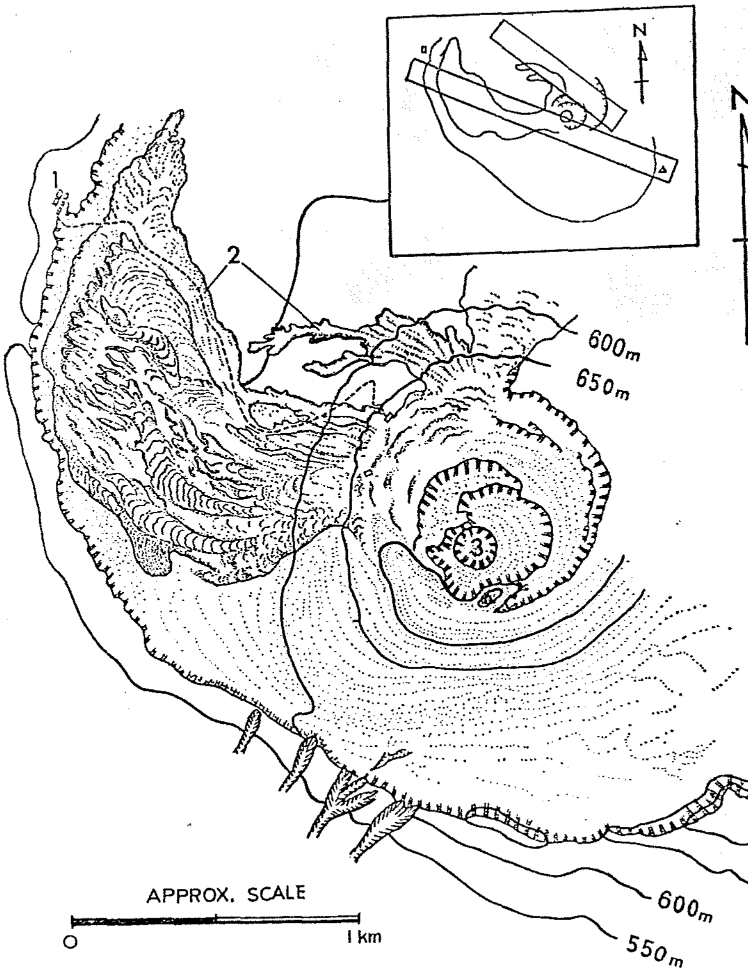


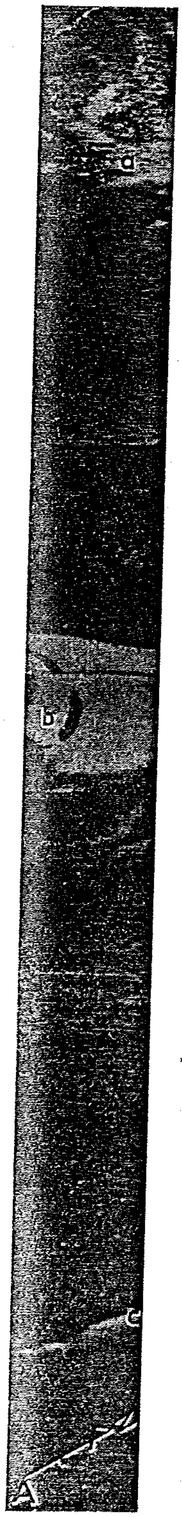
Fig.8. Map of Miharayama caldera, Ooshima Island, showing the area imaged in Plate IA, B. *1* = rest-house Gojinka-jaya; *2* = lava flow formed during the eruption of 1950–1951; *3* = central crater.

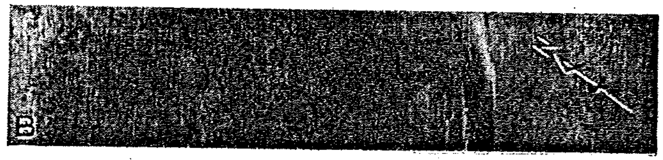
Shear-pattern related to volcanic activity

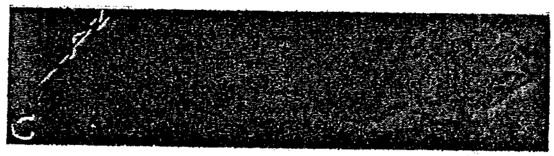
Compared with conventional aerial photographs, an IR image brings quite different information on the earth's surface. Plate IB shows an IR image of the northern portion of the central caldera of Miharayama in which olivine-bearing basalt lava flows and associated fall ashes formed during the eruption of 1950–1951 are distributed as surface materials. On the conventional photographs, the lava flows and fall ashes are quite easily distinguished one from another and their distributions are definitely delineated because of their tonal differences and surface morphological characteristics, namely dark tone and rough surface of lava flows, and gray tone and smooth surface of fall ashes.

On the IR image, however, they can hardly be distinguished because of the lack of differences in tonal density and surface morphological characteristics be-

PLATE I







A. Infrared image of a part of Miharayama caldera shown in Fig.8. Time, 06h15, March 20, 1967; altitude, 1,000 m. a = thermal anomaly on the surface of the lava flow of 1950–1951; b = thermal anomaly on the inner wall of the caldera rim.

B. Infrared imagery permits shear-patterns to be readily discerned.

C. Infrared image showing dispersal pattern of river water into sea water.

tween them. This fact may indicate that there is no difference in emissivity factor between both geologic units in this portion. This image however, permits two systems of linear patterns of a N70°E and N18°E trend, to be readily discerned. These lineations may suggest fractures generated by volcanic explosions in the rocks beneath the surface cover. These lineations are shown as dual lines of lighter and darker tone. The darker toned lines are caused by noise in the sensor amplifier.

Dispersal pattern of river water into the sea

Dispersal patterns of fresh river water into the salt water of the sea is well defined on the IR images obtained from the air because of the temperature difference between them. In Plate IC, an IR image which was provided by an airplane at 1,000 m in altitude above the mouth of the Katase river, is shown. The dispersal pattern of the warmer river water into the colder salt water of the Pacific Ocean is well recorded on the image. Water surfaces are the best objects for observations by an IR imaging sensor from the air, because of their surface flatness.

CONCLUSION

Application of remote sensors to the geoscientific researches on the earth's surface has been in rapid progress since 1961. Among them, observation and mapping of the geothermal distribution of the earth's surface using IR imaging radiometers from remote high altitude is going to be applied to many purposes including geoscientific ones in several countries.

In Japan, airborne IR imaging sensors have been developed by the Nippon Electric Co. and others. It is believed that the mapping potential of large areas by IR remote sensing from the air assists our Geological Survey in the acqusition of data concerning the geothermal distribution of the earth's surface, particularly in relation to the extensive volcanic systems. In the beginning of 1967, the first experimental flight aimed at geothermal observation and mapping were carried out by the Geological Survey of Japan in cooperation with the Nippon Electric Co. and Asia Air Survey Co. as an initial step to "IR geology" in Japan.

For the further development of IR geology, geologic understanding of IR sensor data will be needed as well as development of the ability to collect these data. This source of data will contribute greatly to the geosciences, through combination of laboratory study of interactions of naturally occurring substances with electromagnetic radiant energy and through extensive field appraisals of images obtained by airborne sensors.

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