CHINESE GEOGRAPHICAL SCIENCE
Volume 9, Number 3, pp. 258-264, 1999
Science Press, Beijing, China

STUDY ON TRANSMISSION MECHANISM OF THERMAL INFRARED REMOTE SENSING FOR ABRUPT GEOTHERMAL ANOMALY IN VOLCANIC REGION[①]

Bo Liqun(薄立群) Hua Renkui(华仁葵) Xu Xinliang(徐新良)
Changchun Institute of Geography, the Chinese Academy of Sciences, Changchun 130021, *P. R. China*
Zhou Demin(周德民)
Changchun Branch, the Chinese Academy of Sciences, Changchun 130022, *P. R. China*
(Received 4 June 1999)

ABSTRACT: Experiment researches have proven that there is an obvious phenomenon of abrupt geothermal anomaly in volcanic region in the forewarning period of volcano eruption, which is closely related to the geological structure, the cause, the scale and the type of volcano etc. On the other hand, this kind of geothermal anomaly is an important sign to monitor volcano activity by thermal infrared remote sensing techniques. This paper discusses the feature of abrupt geothermal anomaly, the transmission mechanism of geothermal anomaly and the radiation transmission mechanism of heat field of terrene in volcanic region. By analyzing mechanism of terrene temperature rising by way of conduction and convection of heat, we have presented the transmission equation of atmosphere for thermal infrared radiation based on the effective radiation of objects. The related problems of noise interference in the processes of transmission for thermal infrared radiation will be discussed in the later paper.

KEY WORDS: volcano, abrupt geothermal anomaly, thermal infrared remote sensing

Geothermal anomaly is a phenomenon that underground temperature and geothermal gradient increases much more in the area than its surroundings (Xia, 1979). Abrupt geothermal anomaly means that underground temperature on some spots as well as the affected temperature of surrounding area abruptly increases in a short time. Its geophysics properties represent time and space feature of current underground magma activity or crush movement intensity in the area, which contains much information for geology, geophysics and geo-dynamics. So the above information is very important physical values to monitor and forecast temporary volcanic activity, the expression formula is:

$$\Delta T > \omega$$

where ΔT is an average temperature difference of anomalous and normal area, ω is a threshold value of volcanic activity intensity. The above formula means if the average temperature difference is as high as to a critical value, a certain type of volcano will be probably erupted in some extents. The apparent form of abrupt geothermal anomaly in volcanic region appears as much increase of the geothermal current. The geothermal current (Chen *et al.*, 1994) is represented as unit scattered quantity of heat per unit time from internal to the surface of the earth, which is a comprehensive parameter, having a certain regional representation. It not only reflects deep or shadow thermal statues, but also is of important significance to study new structure motion, hydro-geological

① This project was supported by the Science and Technology Committee of Jilin Province (No. 980356).
© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

condition as well as geothermal anomalous cause of formation in anomalous region's surroundings. In the forewarning period of volcano, the geothermal current in anomalous region is higher than in normal region because of the abrupt geothermal anomaly. After the geothermal current reaches the surface of earth, it will radiate to the sky in the form of radiation transmission, through atmosphere layer, accepted by thermal infrared sensor. So accepted values for temperature difference, combined with other geophysics parameters such as earthquake, crush deformation, geomagnetism, crush stress etc., perform real monitoring for volcano activity. This is a theoretic base of monitoring volcano activity by thermal infrared remote sensing techniques.

As studied by Rybach and Muffler, geothermal feature varies as the times, scale and type of volcanic activity. For this reason, when we study remote sensing monitoring for abrupt geothermal anomaly, we must be aware of different types of volcanic abrupt geothermal features. Next, different volcanic construction, geology structure, volcano surrounding rock and soil layers have its own thermal anomaly. Knowing geothermal transmission mechanism under various conditions is necessary to accurately monitor and forecast volcanic activity. Finally, in the process of geothermal field transmission towards atmosphere, the geothermal field will be interfered by various factors. Deeply studying thermal radiation transmission and various interfere noises in anomalous region is also a key content of thermal infrared remote sensing monitoring. This paper discusses the thermal infrared remote sensing mechanism of the thermal transmission and radiation of abrupt geothermal anomaly.

1 FEATURES OF ABRUPT GEOTHERMAL ANOMALY IN VOLCANIC REGION

According to the slab theory, volcano emanation is a form of strong release of substance and energy inside the earth. When cold oceanic slabs go down to one side of island arc from oceanic trench, during the initial period, volcanic activity could not be caused in virtue of low temperature. Crush materials melt under the action of various stresses at a specified distance and depth of the slabs (You *et al*., 1998). Thus, melting substances will erupt from rock faults or rupture belts under the action of high pressure (Song *et al*., 1990; Jin *et al*., 1994). During the development of volcano, abrupt geothermal anomaly definitely occurs at repeated times, however, pocket of magma detained at shadow crush is only the ideal hot spot source of geothermal anomaly in volcanic region. Deep melting magma in the course of moving up by high pressure excites pocket of magma. Therefore, the existed anomalous subterranean heat is aroused into abrupt geothermal anomaly. Different types of volcanoes have different geothermal features. Studying different types of geothermal features and intensity of volcano activity is one of thermal infrared remote sensing monitoring and forecasting.

1.1 Volcanic Position at Global Structure Determines Geothermal Global Layout

Slab boundaries and its surrounding regions are one of the strongest areas in the global structure activity, which are able to present the high heat flow anomaly. This kind of anomaly mostly produces intense water heat activities and geological structure conditions and heat background necessary to high temperature water heat system. This also is the biggest temperature difference area between anomalous and normal region, in which formation and expansion of high temperature geothermal belts are closely linked with the occurrence, development and evolution of lithosphere. Belt's construction moves violently, age of heat events is less, and ground heat flow values are higher. High temperature belts are generally located near the boundary of every big slab. Inversely, in vast areas far away the boundary of slabs the construction moves weakly, and becomes relatively stable slabs. Heat background tends to the low side, and coefficients of water heat also decrease. In general, there is a low and middle temperature belt to be formed, whose distributions have something to do

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

with moving faults inside slabs and development and evolution of the sedimentary basin. For instance, heavenly pool volcanoes at the Changbai Mountain lies at 1300 km west to the collision boundary between pacific oceanic and Eurasian slabs. Volcano activity not only concerns with slab movement, but also deep-big fault movement inside slabs. Moreover, water heat activity in volcanic region features with underground water emergence and other surface heat preserntation. Appearance spots of these surface heats just are the most sensitive place for abrupt geothermal anomaly in volcanic region. At once abrupt geothermal anomaly comes out, the temperature will obviously go up.

1.2 Age, Scale and Type of Volcano Activity Restrict Geothermal Regional Layout

The newer age and the bigger scale of volcanic activity is, the more possible the formation of high temperature anomaly. From the view of global, dejected or expanding acid volcanoes are interrelated with the high temperature water-heat system, while basic volcanoes in slab not. This is because rocks erupted by basic volcanoes have vanished by the remaining heat of rock bodies. Pocket of magma necessary to form the high temperature water-heat system is not held up in the crushed shadow of volcanic region, so that there is not a direct heat source to increase ground temperature. Volcanic region at Changbai Mountain fully reflects this feature. Before 2 Ma volcano of Changbai Mountain erupted mainly on crack; afterwards, it changed into central acid eruption, and pocket of magma would be found at 15km depth of heavenly pool. The characteristics might become an ideal condition providing to forecast the abrupt geothermal anomaly prior to volcano eruption.

1.3 Factors of Non-volcanic Activity Affect Abrupt Geothermal Anomaly

Elements such as U, Th, ^{40}K etc. in crushed rocks are able to generate certain ground heat currents by decay, which probably covers up the abrupt geothermal anomaly. The surface conditions and geological processes have a function to alter shadow ground temperature fields and heat current distributions, such as deposit and disintegration, settlement and lift, palaeoclimate and rock thermal physics feature. In addition, lithological characters and hydrologic features in volcanic regions also directly affect geothermal anomaly.

2 TRANSMISSION MECHANISM OF GEOTHERMAL ANOMALY IN VOLCANIC REGION

The deep terrestrial heat in volcanic region might be transmitted to surface through various mechanisms. During the rest period of volcano, volcanic areas have a phenomenon of geothermal anomaly; while in mobile or forewarning period, geothermal anomaly would be more obvious to show off. In the course of transmitting to surface, deep terrestrial heat mainly transmits through electromagnetic radiation, conduction of heat, convection of heat etc. towards the surface, which makes the temperature of surface rise. Besides, the sun's radiation also has a certain role on the surface temperature rising.

2.1 Temperature Rising by Absorbing Electromagnetic Radiation

Slabs in rock layers bear the actions of structure stress, so that they determine state of stress. Structure stress includes two categories: the volume force and the surface force. The volume force acts at inner of the whole rock slab, its strength is directly proportional to its volume and quality of trace element, including gravity and inertia force produced by the rotation of the earth. The surface force is formed by the applied force among atoms inside substances, which is proportional to surface areas applied, and related to direction of surface. Structure stress can be expressed by the following equation (Ma, 1997):

$$F = \frac{\mathrm{d}Fex}{\mathrm{d}s}$$

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

where Fex is outer force, s as curve surface forced. In general, direction of geological force is oblique to the surface, F can be divided into two sub-forces, one is positive force; the other is cutting force τ, while $\tau = 0$, $\Delta\sigma_{xx}$ positive force as main force. The equation is as follows:

$$\Delta\sigma_{xx} = \frac{g^2 \cdot \rho_a \cdot U}{4\pi \cdot f \cdot \rho_m \cdot \rho}$$

where U represents a vertical bias, $U = U''/\rho''$, $\rho'' = 206\,265$, ρ_a、ρ_m is separately regional density and mantle density, g as normal gravity value, f as constant. We will draw out dynamical curve of stress force in volcanic anomalous region by the above equation, which may assist to monitor volcano activity. In this way, rocks will produce elastic and spring morphological change under the common action of various stresses. In the process of motion, morphology and rupture of rock slabs, rock substances will adjust their inner structure and produce some physics and chemistry phenomena. The inner mechanics energy will be transformed into heat energy, and appears as electromagnet waves. In the birth of volcano and earthquake, crust stress changes a lot, so that rock temperature will rise in a large area. The high energy released to space along with crack and rift results in temperature rising in a larger surface.

In addition, partial energy may penetrate through surface, and directly enter into lower layer atmosphere. With earth substance temperature rising, inner electrons have enough motive energy to release out of rock surface, and enter into atmosphere. These free electrons affect the change of low atmosphere static field, and the electrons act with the protons released by the sun to make surface temperature rise.

2.2 Conduction of Heat

In solid, normalization of temperature is completed through the action among the crystal grid (molecule), so we call heat energy of molecule moving from one area to another as conduction of heat (Lu *et al.*, 1998). Suppose $T(x, y, z, t)$ can be used to describe the time and space distribution of temperature, heat always flows from higher area to lower area in the heat field, and the higher difference of temperature is; the faster motion of heat. Suppose taking geothermal anomaly area as a temperature field, while ds represents any curves in the field, and n as a direction of normal line, according to the theory of conduction of heat, we get:

$$dQ = -k(\partial T/\partial n) \cdot ds \cdot dt$$

when $\partial T/\partial n$ is negative and n gets smaller, dQ will be positive. If q represents heat vector, then:

$$q = -k \cdot gradT$$

where $k(> 0)$ is a coefficient of conduction of heat, unit is J/(m·s·k); $gradT$ represents the gradient of temperature. This equation shows that the heat flux of vertical direction is directly proportion to the gradient of temperature within crust. When the heat flux is constant, the ratio of heat conduction in medium is adversely proportion to the gradient of temperature in value, that is, the lower ratio of heat conduction is; the higher the gradient of temperature is, the heat in medium hardly sends out.

Any area V taken in a closed curve S, in certain time dt, the heat flowing from area V to curve S may be defined as:

$$Q = -dt \cdot \iint k \cdot gradT \cdot ds$$

where $gradT = (\partial T/\partial n) > 0$, that is, the temperature along with the outer direction of normal line goes up. We may infer the following equation from the above (Ma, 1997):

$$Q = dt \iiint div\ (k \cdot grad\ T)\,dv$$

div represents divergence. Suppose ρ is used as substance density, Υ_H as specific heat volume, in certain time, the temperature increment of substance volume will be:

$$dT = (\partial T/\partial n) \cdot dt$$

So heat quantity of volume elements may be represented as:

$$\Upsilon_H \cdot \rho \cdot dv \cdot dT = \Upsilon_H \cdot \rho \cdot dv \cdot (\partial T/\partial n) \cdot dt$$

Absorbing quantity of heat in the whole area is:

$$Q' = dt \cdot \iiint \Upsilon_H \cdot \rho \cdot (\partial T/\partial n) \cdot dv$$

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

According to the theory of energy balance, we may deduce:

$$\iiint \Upsilon_H . \rho \cdot (\partial T/\partial n) \cdot dv$$
$$= \iiint div\ (k \cdot gradT) \cdot dv$$

Since this equation adapts to any area within substance, it can result in the following differential equation:

$$\Upsilon_H \cdot \rho \cdot (\partial T/\partial n) = div(k \cdot gradT)$$

The above equation is called as the equation of heat conduction. In fact, the substance from underground to surface is not well-distributed, different rocks and soils have different rate of heat conduction and density because of their structure. In practice, any physical analysis of characteristics to stratigraphical lithological characters and soil texture in volcano area must be based on stratigraphical maps, geological maps, geological maps of the Quaternary Period and soil texture maps etc. In general, these geological physical parameters are a part of background databases for remote sensing monitoring. In the forewarning period of volcano activity, temperature rising resulted in by abrupt geothermal anomaly may be detected by thermal infrared sensors. Temperature difference between anomalous and normal areas can be used to analyze geothermal anomaly, which may efficiently avoid complex of the above mathematics computation.

2.3 Convection of Heat

Most geothermal energy can be converted through the underground water and the magma motion. When hot sticky magma suddenly touches cold circulation layers, a great deal of volatile flux will be produced and underground water will be heated. In addition, while volcano activity is active, the temperature of original hot spring and crater lakes must be rising. In this case, heat transmission in water body mainly depends upon heat exchange. Produced volatile flux and heated gases such as vapor, hydrogen, HCl, CO_2, CO, H_2S, SO_2, HF etc. contained in magma and adjoining rocks will be released to air through movement faults and broken rock cracks. They not only bring heat to surface, but also result in the hothouse effect in basin and low gully, which will make temperature rise in the area.

2.4 Radiation of Sun

In days the surface of earth radiated by the Sun makes its temperature rise. In the forewarning period of volcano activity, substance structure and state will be changed because of the affection of geothermal anomaly. The temperature rises more in anomalous region than in normal region by the radiation of the Sun. This is because a great deal of high temperature's magma goes up to crush and heats country rocks. Vapors in country rocks and soils greatly evaporate. When they meet chilled junction in the surface, it will make the content of water in substance in the surface of the earth increase, which can change the structure of water layers of soils and rocks, and get heat capacity of substance larger. This shows that substances are very capable of storing heat. There is an obvious and different temperature indicator between anomaly and normal areas.

In summary, we can prove that, according to the above transmission mechanism, there is an obvious increase in surface's temperature in abrupt geothermal anomalous area in contrast to geothermal normal area in the forewarning period of volcano activity. In the view of formation cause and geothermal transmission mechanism of abrupt geothermal anomaly in volcano area, rising range of temperature in anomalous area could be from 3 to 6 degree centigrade or more. This offers a basic condition for monitoring volcano activity by thermal infrared remote sensing techniques.

3 RADIATION TRANSMISSION MECHANISM OF HEAT FIELD OF TERRENE

Atmosphere gathers in space from the surface up to 300 km, but remote sensing satellite orbits about 800 km. Heat radiation of the earth's surface must

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

penetrate through atmospheric layer, and reach the sensors of the satellite. However, the sensors just receive the effective part of radiation.

3.1 Effective Radiation of the Ground

Radiation can be regarded as the function of structure and temperature by substances for emission. Every substance whose temperature is above absolute zero will emit electromagnetic radiation, the expression formula is:

$$E_s = \varepsilon \cdot \sigma \cdot T^4$$

where E_s is radiation ability; ε emission rate; T absolute temperature and σ constant equal to 0.817E-10 K/cm^2 • M • C. From the above equation we may see that emission ability of substance is proportional to the fourth power of temperature. The higher the temperature rises in anomalous area; the greater the ability of emitting electromagnetic wave is. According to Verne's law of displacement, the wavelength λ_m of the greatest radiation ability may be represented as:

$$\lambda_m \cdot T = 2898 \mu m \cdot c$$

This expression shows that the wavelength of the greatest radiation ability should stay in thermal infrared range from 8 to 14 μm, usually called long-wave radiation. Only in the short period of volcano eruption can the wavelength move up to 3 μm middle infrared spectrum. Most long-wave radiation will be absorbed by atmosphere, while only a small part can directly get up to space, so that the sensors just record the effective radiation values from the earth's surface, the formula can be represented as follows (Zhou *et al*., 1994):

$$F = E_s - \varepsilon E_a = \varepsilon(\sigma T^4 - E_a)$$

where F is effective radiation, E_a inverse radiation of atmosphere. Unfortunately in most case recorded data are not radiation flux, but radiation temperature:

$$T_{rad} = \varepsilon^{1/4} \cdot T_{kin}$$

where ε is emission rate, T_{kin} is the temperature of molecule motion. Therefore, values recorded by sensors can decide the temperature difference between anomalous region and normal region, which can be used to analyze the characteristic law of geothermal anomaly.

3.2 Transmission of Effective Radiation of the Ground

In the process of transmission of the ground heat radiation to sensors, absorbing and scattering of atmosphere media will surely occur. Even in the range of "atmosphere window" (8.5-14 μm) it is not completely transparent. Except for absorbing and scattering, atmosphere itself emits the long-wave radiation. Figure 1 shows the transmission process of thermal infrared radiation of terrene.

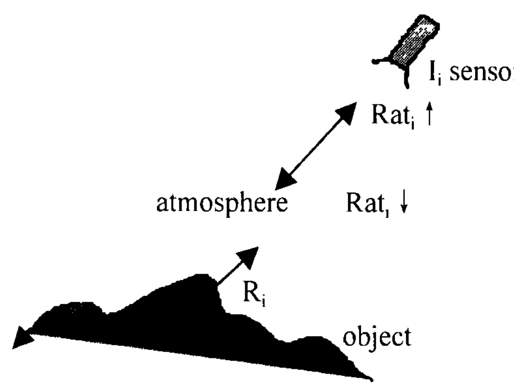

Fig. 1 Sketch map of atmosphere transmission

I_i of Fig. 1 represents the thermal infrared radiation received by sensors, R_i is values of thermal radiation of objects, Rat_i ↑ thermal radiation up at band i of atmosphere, Rat_i ↓ down at band i. Then:

$$R_i = \varepsilon \cdot B_i \cdot (T_s) + (1 - \varepsilon) Rat_i \downarrow$$

In equation, T_s is the temperature of objects, ε_i as an emission rate at band i. Suppose atmosphere consists of n layers; d_i as thickness; T_i as temperature and K_i as attenuation coefficient; and each layer is regarded as uniform one, and absorbing and scattering of atmosphere is neglected, a transmission model of atmosphere is expressed as follows (Zhang, 1996):

$$M_\lambda(h, \theta) = M(0, \theta) \exp\left(-\sum_{j=1} K_j \cdot d_j / \cos\theta\right)$$

$$+ \sum_{i=1}^{n} \left(1 - \exp(-K_j \cdot d_j / \cos\theta)\right) \exp$$

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

$$(-\sum_{j=i+1}^{n} K_j \cdot d_j / \cos\theta) \cdot M^0_\lambda(T_i)$$

where $M_\lambda(h, \theta)$ represents the density of radiation flux obtained by sensors, h is altitude, θ as the angle of observation. It has been shown from the above formula that radiation flux received by sensors contains the radiation of both terrene and atmosphere. If specific radiation rate is bigger than 0.989 (based on body of water, wet soil and vegetation), the temperature recorded by sensors at a certain altitude can be written as:

$$T(z, \theta) = T_s + (AW(h)/\cos\theta) \cdot (\theta(z) - T_g) + \varepsilon_{cor}$$

In formula, Z is an altitude; θ is an angle of observation; T_s as the temperature of radiation of terrene; as the whole content of vapors at h altitude; A is a characteristic constant of atmosphere; ε_{cor} is a corrected value of specific radiation rate. Thus, the effective temperature of atmosphere can be represented as:

$$\theta(z) = \sum_{i=1}^{n}(W_i T_i) / \sum_{j=1}^{n}(W_j)$$

A is related to the contents of vapors, the altitude of sensors and the angle of observation. So radiation's temperature of objects may be formulated:

$$T_s = T(z, \theta) - (AW(h)/\cos\theta) \cdot (\theta(z) - Tg) - \varepsilon_{cor}$$

In formula, the value of temperature directly reflects the distribution of heat field of terrene.

The above formula is valid just when no noise exists. In fact, there are a lot of noise sources in nature. Much more researches will be required in later work.

4 CONCLUSION

Monitoring volcano activity by remote sensing techniques is at the initial stage of research in China. This paper discusses characteristics shown by abrupt geothermal anomaly, geothermal transmission mechanism and heat radiation transmission mechanism, which are a basic problem to monitor volcano activity by remote sensing techniques. The objective is to offer a few commonplace remarks by way of introduction so that others may come up with valuable researches in the near future. Especially in the field of noise-removal, author is eager to cooperate with the persons who are much interested in it.

REFERENCES

Chen Moxiang *et al.*, 1994. *Formation Character and Potential Appraisal on Geothermal Resources of China*. Beijing: Chinese Science Press, 1-38. (in Chinese)

Jin Bolu *et al.*, 1994. *Study on Volcanic Geology of Changbai Mountain*. Yanji: Northeast Korean Nationality Education Press, 71-72. (in Chinese)

Lu Guxian *et al.*, 1998. Study on heat conduction and temperature changes for heat source bodies in structure rock belts. *Acta Geoscientia Sinica*. 19(2): 138-143. (in Chinese)

Ma Ainai, 1997. *Remote Sensing Information Model*. Beijing: Peking University Press, 108-111. (in Chinese)

Song Haiyuan *et al.*, 1990. *Study on Volcanoes of Changbai Mountain*. Yanji: Yanbian University Press. (in Chinese)

Xia Zhengnong, 1979. *Lexicon*. Shanghai: Lexicon Press.

You Yongxiong *et al.*, 1998. Monitoring earthquake's forewarning field in the northwest of Yunnan Province by remote sensing techniques. *Science in China (D edition)*. 28(4): 340-345. (in Chinese)

Zhang Renhua, 1996. *Experiment Remote Sensing Models and Ground Base*. Beijing: Science Press, 88-89. (in Chinese)

Zhou Shuzhen *et al.*, 1994. *Meteorology and Climatology*. Beijing: Higher Education Press, 49-53. (in Chinese)

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net