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Remote sensing for geothermal applications

Remote sensing can contribute to geothermal studies and exploration by detecting surface thermal anomalies by the use of thermal infrared imagery, mapping lineaments that are conduits for geothermal fluids, depicting the regional volcanic framework, and delineating hydrothermally altered areas by the use of spectral patterns in the short-wave-infrared regions. In particular, the Optical Sensor on the Japanese Earth Resources Satellite, launched February 11, 1992, will be useful for discriminating hydrothermal alteration zones. Another future remote sensor that will be applicable to geothermal surveys is the Advanced Spaceborne Thermal Emission and Reflection radiometer, a research facility instrument that will be launched in 1998 on the United States National Aeronautics and Space Administration's Polar-Orbiting Platform.

Introduction

Geothermal energy is one of the alternative energy sources that is being used in various ways, including for electric power generation and local heating systems. Countries like the United States, Philippines, Mexico, Italy, New Zealand, Japan, Indonesia, El Salvador, Kenya, Iceland, Nicaragua, Turkey, China, and Russia are operating geothermal power plants. The world's total electric output from geothermal energy reached approximately 6,000 megawatts in 1989. The majority of the current geothermal power plants are using high-temperature fluids that are composed of hot water and steam.

In Japan, most hydrothermal convection systems are developed in areas related to Quaternary volcanism, and these systems are associated with surface activity such as hot springs, fumaroles, hydrothermal alteration, and anomalously high surface temperatures, which can be the targets for remote sensing. For instance, remote sensing techniques have contributed to national and regional geothermal surveys by detecting topographic features related to geothermal activities and by detecting surface thermal anomalies by the use of thermal infrared imagery. These techniques also are used to map and discriminate hydrothermally altered areas that produce spectral patterns in the visible to short-wave-infrared regions. This paper provides some examples of the remote sensing methods that have been applied to geothermal studies and exploration, and we discuss the future trends in this area.

Mapping surface thermal anomalies

The first application of thermal infrared imagery to detect thermal anomalies in volcanic areas was done by Fischer and others (1964).

In Japan, an experimental study employing a laboratory-use, prototype thermal infrared imaging instrument was started in 1965 on some Japanese geothermal fields by members of the Geological Survey of Japan and the NEC Corporation. These tests were successful in obtaining useful data. In the following year, an airborne single-band thermal infrared scanner was constructed (Matsuno and others, 1969), and the scanner continued to be improved by the NEC Corporation until 1968. However, more advanced imaging scanners were developed by the United States and Sweden, and these were used in the early stage of regional geothermal studies (Hase, 1971, 1974).

For instance, the thermal infrared image (fig. 1) obtained in the Sengan area, one of the most promising geothermal fields in northern Japan, was used for historical thermal evaluation of the geothermal activity by measuring the area of "dead" and "live" geothermal phenomena (Hase and Miyazaki, 1988). Geothermal activity at Fukuonoyu hot spring in the center of the area is known to wander about because of the sealing effect of hydrothermally altered soil and (or) rocks. This wandering seems to be rather common and is observed in many geothermal areas. The extent of the geothermally anomalous area was measured on the thermal infrared imagery and then was compared to the surrounding hydrothermally altered background area. The empirical field study, which found the limits of detectable thermal anomalies at the natural geothermal surface in terms of heat flow, showed a range of 200 to 800 $\mu\text{cal}/\text{cm}^2 \text{ s}$, and the surveys effectively mapped the geothermally anomalous surface beyond this heat intensity (Hase, 1974).

Another example of mapping surface thermal anomalies was presented by Kawamura and Yamaguchi (1982), who studied the Onikobe geothermal area in northern Japan by using an airborne thermal infrared scanner. As most of this area is covered by thick vegetation, an interpolation method that makes use of the double Fourier progression was employed to infer the ground-surface temperature distribution from the data of open bare ground.

In addition, multiband sensors in the thermal infrared region have been developed. These make it possible to know the spectral emittance patterns of surface material, as well as provide more accurate surface temperatures. The Thermal Infrared Multispectral Scanner (TIMS) developed by the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) (Kahle and Goetz, 1983) and the Geoscan Airborne Multispectral Scanner (AMSS) (Honey and Daniels, 1985) are examples of the multiband thermal infrared imager. Japan is developing a multiband thermal infrared sensor known as the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), which is detailed later in this article.

Lineaments as conduits of geothermal fluids

Lineaments interpreted from remotely sensed imagery provide important information on subsurface fractures that may control the convective movement of geothermal fluids. In the summer of 1980, the Japanese New Energy Development Organization (NEDO) car-

A

B

Figure 1.—Goshogake in the Sengan geothermal area, northern Japan. A, Thermal infrared image of the area. B, Interpretation of the thermal infrared image. Dotted areas are thermal anomalies. Abbreviation: hotsp, hot springs.

ried out an airborne Synthetic Aperture Radar (SAR) mapping survey over all the Japanese islands. Yamaguchi and others (1985) interpreted the lineaments from the SAR images obtained in this project, and they made a detailed field survey of a set of specific lineaments for the Hoho geothermal area in southwestern Japan. The test area for this geothermal assessment is covered mostly by vegetation and young volcanic ash deposits. A soil-gas method was employed at several survey lines across the lineament trace, and it showed concentrations of radon and CO_2 . Although the soil gas was not of deep origin, as determined from analysis of the gas constituents measured by gas chromatography, the anomalously high radon and CO_2 indicated the existence of a concentration mechanism of radioactive materials and biochemical activation. This concentration mechanism suggests the existence of subsurface fractures.

Regional volcanic framework

Many hydrothermal convection systems are situated at or near Quaternary volcanoes in Japan, and photogeologic interpretation is quite helpful in volcano-stratigraphic studies of these areas. Molten or solidified magma beneath such areas generally is accepted as the heat source for the volcano-related geothermal systems.

Large-scale circular features are observed in volcanic terranes from synoptic Landsat imagery. These features are known sometimes to be Quaternary calderas. Other features are concealed partly by sediments or are obscured by dissected geomorphology. The Okiura area in the northernmost part of the main island of Japan was studied in order to (1) clarify the geologic meaning of its large circular

feature and (2) assess the geothermal potential of the area. The researchers concluded that the area was the center of early Pleistocene, large-scale volcanism and that the circular feature is a caldera, which was formed by the eruption of voluminous acidic tuff and was given the name of Okiura caldera (Muraoka and Hase, 1981). The Okiura area was selected as a geothermal exploration target. A combination of several new types of data obtained in drilling and in the assessment of geothermal resources assisted in interpreting the caldera structure.

Landslide topography also is observed on remotely sensed imagery in volcano-related geothermal areas. In the Sengan area, the geothermally active spots are located in landslide areas (Hase and others, 1983). Lineaments mapped on initial volcanic surfaces are the straight segments of streams as opposed to consequent streams. Valley heads of landslide topography have, in many cases, straight escarpments and correspond to lineament directions. The SAR image demonstrates the situation where the collapse of volcanic bodies is accelerated by the development of fractures and circulation of geothermal fluids along fracture systems below the young volcanic ejecta.

Detection of hydrothermal alteration: JERS-1 OPS

A hydrothermally altered area is a typical surface manifestation of geothermal activities and is, therefore, an important target for remote sensing techniques applied to geothermal areas. Multiband sensors in the short-wave-infrared region should be useful for mapping hydrothermal alteration halos because phyllosilicate minerals exhibit diagnostic absorption features in the short-wave-infrared region.

The Optical Sensor (OPS) of the Japanese Earth Resources Satellite (JERS-1), which was launched on February 11, 1992, has four bands in the short-wave-infrared region and four bands in the

Figure 2.—Reflectance spectra of selected minerals and the band passes (1–8) of JERS-1 OPS. Explanation: a, kaolinite; b, montmorillonite; c, alunite; d, calcite. Spectra are displaced vertically, and 20 percent indicates percent reflectance.

Table 1.—Major characteristics of JERS-1 sensors

System	Subsystem	Band no.	Spectral range (μm)
OPS	Visible to near-infrared	1	0.52–0.60
		2	0.63–0.69
		3	0.76–0.86
		4	0.76–0.86 (forward viewing)
	Short-wave-infrared	5	1.60–1.71
		6	2.01–2.12
		7	2.13–2.25
		8	2.27–2.40
SAR	Item	Performance	
	Ground resolution	18.3×24.2 m	
	Stereo B/H ratio	0.3	
	Swath width	75 km	
	Digitization	6 bits	
	Data rate	60 Mbps	
	Frequency	1275 MHz (L-band)	
	Ground resolution	18×18 m (3 looks)	
	Off-nadir angle	35 degrees	
	Swath width	75 km	
	NEΔp	–20.5 dB maximum	
	Transmitting power	Approximately 1.3 kW	
	Digitization	3 bits	
	Data rate	60 Mbps	

visible to near-infrared region including one forward-viewing band for stereoscopic imaging along the nadir track of the satellite (table 1). The visible to near-infrared bands have band passes similar to those of the Landsat Thematic Mapper (TM), whereas OPS bands 6, 7, and 8 in the short-wave-infrared region are three subdivisions spectrally of TM band 7. As shown in figure 2, the OPS short-wave-infrared bands are clearly targeting the absorption features of phyllosilicate and carbonate minerals for the purpose of lithologic mapping. According to a preliminary investigation that used simulated OPS response patterns (Yamaguchi, 1987), we can expect that the OPS data will allow us to distinguish three different alteration types: the alunite-pyrophyllite group, the kaolinite-montmorillonite-sericite group, and the epidote-chlorite-carbonate group. Figures 3 and 4 show the simulated OPS images of the Yerington and Silver Bell areas, western United States, from the airborne multispectral scanner data (Akiyama and others, 1989), where the different lithologies and alteration types are displayed in different colors. This proves the usefulness of the OPS for discriminating hydrothermally altered areas.

A future remote sensor: ASTER

One of the future remote sensing systems that will be useful to geothermal applications is ASTER, formerly known as Intermediate and Thermal Infrared Radiometer (ITIR). ASTER is a research facil-

Figure 3.—A JERS-1 OPS simulation image of the Yerington area, Nevada, USA. Band 6 shown as blue, band 7 shown as green, and band 8 shown as red. Decorrelation stretching has been applied (Akiyama and others, 1989).

ity instrument proposed by the Japanese Ministry of International Trade and Industry (MITI) to be launched on NASA's Earth Observing System AM1 (EOS-AM1) platform in 1998 (Yamaguchi and others, 1991). The ASTER inherits the technologies that were developed for the JERS-1, and it is being designed in order to meet the requirements given by the ASTER science team. Table 2 shows its major performance requirements. The ASTER instrument is a multi-spectral imaging radiometer that has 14 spectral bands and consists of 3 subsystems: the visible to near-infrared, short-wave-infrared, and thermal infrared subsystems. All three subsystems will cover the same 60-km imaging swath and have a pointing capability in the crosstrack direction within a range of 232 km. ASTER has three bands in the visible to near-infrared region, six bands in the short-wave-infrared region, and five bands in the thermal infrared region, and these have 15-, 30-, and 90-m ground resolutions, respectively. In addition, ASTER has one backward-viewing visible to near-infrared band for stereoscopic observation in the along-track direction.

ASTER will provide surface-temperature and emissivity data at the highest spatial resolution among all the EOS-AM1 instruments. High spatial resolution data in the visible to near-infrared and short-wave-infrared regions will be obtained within the same 60-km imaging swath as in the thermal infrared bands. Because these data have a wide spectral coverage and relatively high spatial resolution, we will be able to discriminate a variety of surface materials and reduce the problems resulting from mixed pixels.

For geothermal applications, the thermal infrared data will provide surface-temperature information. In very high temperature areas like a lava lake in the crater of an active volcano, the short-wave-infrared bands can measure surface temperature. Therefore, geological mapping will be carried out efficiently by combining the high-resolution stereo data obtained by the visible to near-infrared bands, information on alteration mineralogy recorded by the short-wave-infrared bands, and temperature and emissivity data provided by the thermal infrared bands.

Table 2.—ASTER baseline performance requirements

Subsystem	Band no.	Spectral range (μm)	Radiometric resolution	Spatial resolution
Visible to near-infrared	1	0.52–0.60	≤0.5%	15 m
	2	0.63–0.69		
	3	0.76–0.86		
Short-wave-infrared	4	1.60–1.70	≤0.5%	30 m
	5	2.145–2.185	≤0.8%	
	6	2.185–2.225	≤0.8%	
	7	2.235–2.285	≤1.0%	
	8	2.295–2.365	≤1.0%	
	9	2.36–2.43	≤1.3%	
Thermal infrared	10	8.125–8.475	≤0.3 k	90 m
	11	8.475–8.825		
	12	8.925–9.275		
	13	10.25–10.95		
	14	10.95–11.65		
Item			Performance	
Stereo B/H ratio			0.6	
Swath width			60 km	
Total coverage in crosstrack direction by pointing capability			232 km

Conclusions

Geothermal energy has been attracting public attention lately because it discharges a smaller amount of CO_2 into the atmosphere than hydrocarbons discharge. Therefore, as geothermal studies become more necessary, remote sensing techniques will contribute more to these geothermal studies, as shown here. In the near future, when more advanced sensors like ASTER become available, our understanding of geothermal systems will increase.

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