

THERMAL CAMERA IMAGING OF ROCK PILES AT THE QUESTA MOLYBDENUM MINE, QUESTA, NEW MEXICO¹

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Abstract. Between 1969 and 1981 open pit methods were used to recover the molybdenum ore producing some 317.5 million metric tons of mined rock from the Questa molybdenum mine, which went into nine rock piles. The mine is located in the Sangre de Cristo Mountains of Taos County in northern New Mexico. As part of a multi-disciplinary study to determine the effects of weathering on the long-term stability of the rock piles, we are searching for areas where weathering is occurring within the rock piles. Pyrite oxidation is a weathering process that typically generates large amounts of heat, making it a good candidate for detection by infrared thermography. We conducted surveys of surface temperatures on two rock piles during February and May 2004 using the FLIR SC 3000 infrared thermal camera.

Thermal imaging of the rock piles revealed at one rock pile, a “heat vent” of roughly 40 m by 30 m that had the same maximum temperature of 18°C during February and May 2004. The maximum temperature of this heat vent was much larger than the ambient temperature in February (0-2°C) and May (4-6°C). During the February survey, the heat vent had little or no snow cover and appeared to be very wet, whereas the area surrounding the heat vent was snow-covered and frozen at the same time. The heat vent is likely the result of pyrite oxidation within the rock pile. Thermal imaging results from a second rock pile indicate that it is less likely to have a heat vent because the differences between the ambient and maximum surface temperature were much less significant. The small temperature difference could be explained by spatial variations in emissivity from local variations in rock thermal properties or moisture content or by a relatively small heat flux out of the rock pile.

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Introduction

Approximately 317.5 million metric tons of mined rocks were produced from open pit mining between 1964 and 1981 at the Questa molybdenum mine, which is located in the Sangre de Cristo Mountains of Taos County in semi-arid northern New Mexico (Fig. 1). Most of the mined rock was placed onto nine rock piles, creating slopes with angles of repose (approximately 36 degrees). Weathering of the mined rock containing small but varying amounts of pyrite, could, over the long term, affect the rock pile's mechanical properties. As part of a multi-disciplinary research project, we are investigating the effect of weathering on the long-term stability of the rock piles by determining their geologic, hydrologic, and geotechnical characteristics.

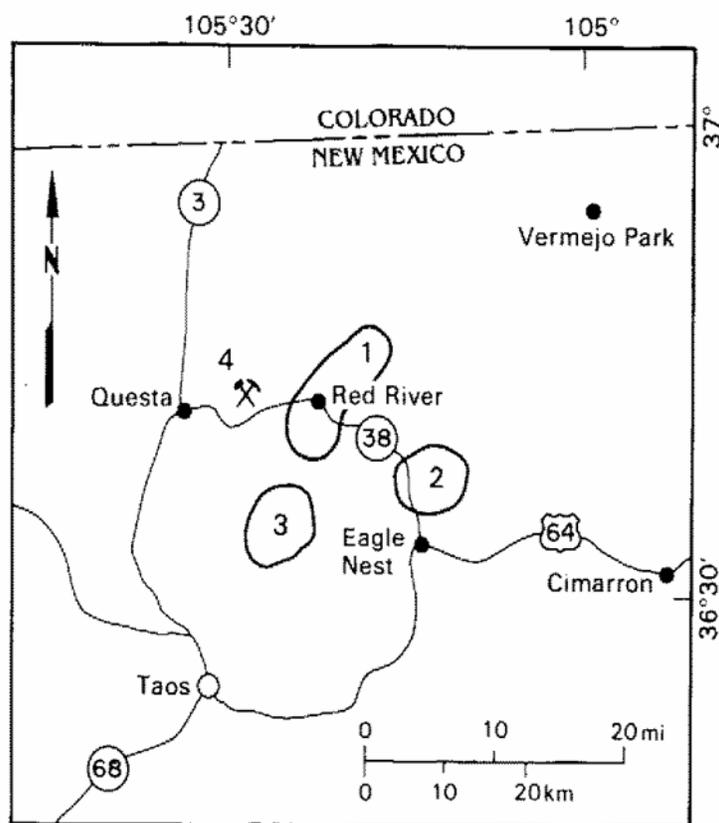


Figure 1. This map shows the Red River mining district of New Mexico, where 1 = Red River mining district; 2 = Elizabethtown-Baldy mining district; 3 = Twining district; and 4 = Molycorp Questa mine.

Historically, thermal imaging has been used in military, industrial, medical, and some scientific work (Hudson, 1969). Infrared imaging systems were first developed by the military and were used in World War II. Technological advances have allowed these systems to be used in new applications. Currently, infrared imaging systems are being used in the medical field to monitor changes in body temperature to aid in diagnosis and treatment planning (Meola and

Carlomagno, 2004). In addition, these systems can be used to monitor ice nucleation and ice propagation in plants (Wisniewski et al., 1997), to monitor pollution of water bodies (Cehlin et al., 2000), to monitor mechanical equipment at electric power plants (Meola and Carlomagno, 2004), and to investigate convective heat fluxes over complicated body shapes (Meola and Carlomagno, 2004). Despite their prevalence in other fields, there is little documentation about the use of these instruments in the earth sciences. One study conducted in the earth sciences was done by Hong et al. (2002) to investigate the possibilities of infrared detection of land mines in bare soils using the daily and annual variations in soil temperature. Hong et al. (2002) concluded that soil surface temperatures exhibit daily and annual variations. Hong et al. (2002) also concluded that the thermal signatures of the buried land mines also showed a cyclic behavior that could be predicted by the physics of the mine-soil-sensor system. Kononov (2000) examined the feasibility of using infrared thermography to detect potential hazards from loose rock in hard rock mines by measuring the temperature gradient between loose and solid rock.

Pyrite oxidation, one of the weathering processes under study, is typically exothermic given sufficient water and oxygen. At present, there is no way to easily identify areas where pyrite oxidation is occurring without excavating the rock pile or without drilling. We used thermal camera imaging (a type of infrared thermography), to locate and quantify temperature differences across areas of the rock piles to lead to a better understanding of the weathering processes occurring within the piles.

Thermal camera surveys were conducted on two of the nine rock piles, Sulfur Gulch South and Goathill North. The Sulfur Gulch South rock pile was selected because we identified an area which appeared to be a possible heat vent and was located near a drill hole (WRD-13) that was venting steam and elevated concentrations of CO₂, presumably a result of pyrite oxidation. Two portions of the Goathill North rock pile were investigated to try to detect evidence of heat vents or thermal anomalies caused by variations in moisture content or gas entering or exiting the rock pile.

Theory of Thermography

Infrared thermography (IRT) is a technique used to collect images which show variations in surface temperature in the infrared spectrum (wavelengths ranging from 1 μm to 0.1 cm). The energy that is emitted from the body being photographed is a function of the surface temperature (Meola and Carlomagno, 2004). One of the principal ways that energy is transferred from the surface of the soil is by radiation (Fig. 2). Radiation refers to the emission of energy by electromagnetic waves from bodies that have a temperature above absolute zero (0°K). The Stefan-Boltzman law:

$$J = \epsilon \sigma T^4 \quad (1)$$

where

J = total emitted energy (W/m²);

T = absolute temperature of the body (K);

σ = Stefan-Boltzman constant (W/m²K⁴);

ε = emissivity of the surface;

indicates that the total energy emitted from a body (J), across all wavelengths is proportional to the surface temperature (T) to the fourth power (Hillel, 1998). The emissivity coefficient ranges

from 0 to 1 and represents the object's ability to emit heat energy. A perfect emitter or a blackbody, which does not reflect energy, has an emissivity coefficient of 1.

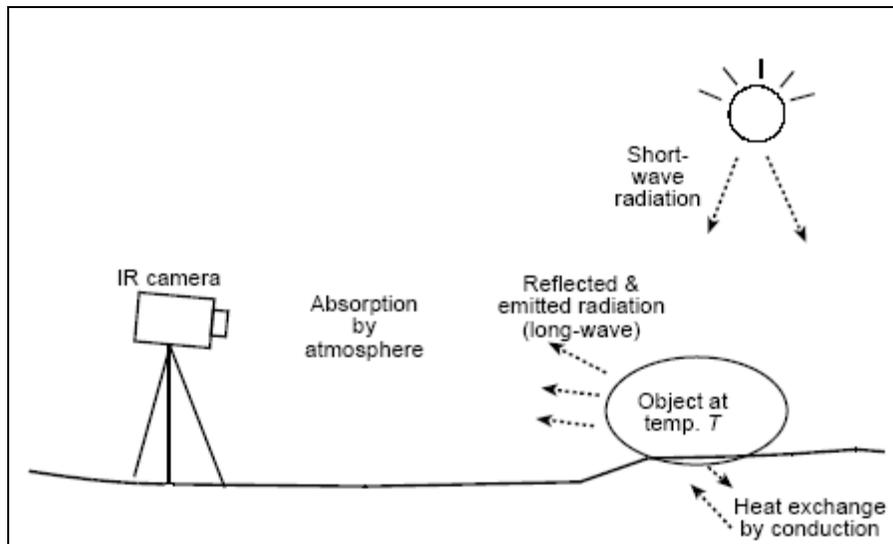


Figure 2. Measuring temperature of a distant object with a radiation thermometer (IR camera).

Three different types of objects can be distinguished by the way the spectral emissivity varies. The first type is a blackbody, which was previously mentioned and for which $\epsilon(\lambda) = \epsilon = 1$. The second type of object acts as a gray body, for which $\epsilon(\lambda) = \epsilon = \text{constant}$ (less than 1). The third type of source is called a selective radiator, for which $\epsilon(\lambda)$ varies with the wavelength (Hudson, 1969).

It is important to note that the emissivity of an object in the visible spectrum is not representative of the object's behavior in the infrared (IR) spectrum. White paint is a good example of how an object can behave very differently in the visible and IR spectra. In the visible spectrum, white paint has a very low emissivity, but in the IR spectrum, the paint has an emissivity approximately equal to a blackbody (Kononov, 2000). The human skin is also an example of the inadvisability of predicting emissivity in the IR spectrum based upon the visual appearance. All human skin, no matter the color, has a very high IR emissivity (Hudson, 1969).

Methods

Site Descriptions

Surface temperatures were mapped at four different survey areas located on the Goathill North (GHN) and Sulfur Gulch South (SGS) rock piles at the Molycorp Molybdenum Mine (Fig. 3). One survey area was located on the SGS rock pile, near a precipitation collector. Three areas were located on the GHN rock pile. Each survey area contained mine rock material removed from the open pit at various times between 1969 and 1981. The specific survey information is presented in Table 1.

Table 1: The site locations and description information. A detailed description of the mapped units can be found in McLemore et al., 2005.

Rock pile	Location	UTM (NAD27)	Dates		Camera Type	Mapped Unit and Description
			surveyed	Time		
SGS	Slope extending from road	13 S 0455238 E 4061441 N	6-8 February 2004	Daytime	Thermal and optical	NA
SGS	Slope extending from road	13 S 0455244 E 4061454 N	19-May-04	2:30 AM to 4:30 AM	Thermal	NA
GHN	Slope of Stable Portion	13 S 0453578 E 4062161 N	20-May-04	2:30 AM to 4:30 AM	Thermal	Unit C, silty sand with cobbles and some gravel
GHN	Slope of Unstable Portion	13 S 0453583 E 4062197 N	20-May-04	2:30 AM to 4:30 AM	Thermal	Unit D, gravelly sand with cobbles and boulders
GHN	Bench and Slope of Unstable/Crack feature	13 S 0453496 E 4062310 N	20-May-04	2:30 AM to 4:30 AM	Thermal	Unit E, sandy-clay with cobbles and boulders

Sulfur Gulch South (SGS) Rock Pile. The survey area on the SGS rock pile (Fig. 3) surrounds a precipitation collector on the middle slope of the rock pile alongside a road at an elevation of 2707 m. Two surveys were conducted on this pile: the first survey was in February 2004 when the surface was partially covered with snow and the second survey was in May 2004, after the snow had melted and the survey area appeared to be relatively dry.

The surveyed area appeared as a relatively wet area of bare rock pile material surrounded by snow-covered areas on 6-7 February 2004 (Fig. 4a). Snow cover increased substantially within rills and on some of the bare rock pile faces sometime between the afternoon of 7 February and the morning of 8 February, presumably by wind-driven re-deposition as no new snow was observed elsewhere (Fig. 4b). The depth of added snow accumulation within the rills was up to 60 cm deep. Ranging in size from fine sand to boulders, the rock pile material was likely near saturation within the topmost 10 – 15 cm at the precipitation collector location and other areas. A relatively small proportion of the bare rock pile was frozen at the surface and was found only on the north-facing sides of ridges and rills. In comparison, the surrounding snow-covered areas appeared uniformly frozen. The survey area was relatively dry and no snow was present during the May 2004 survey.

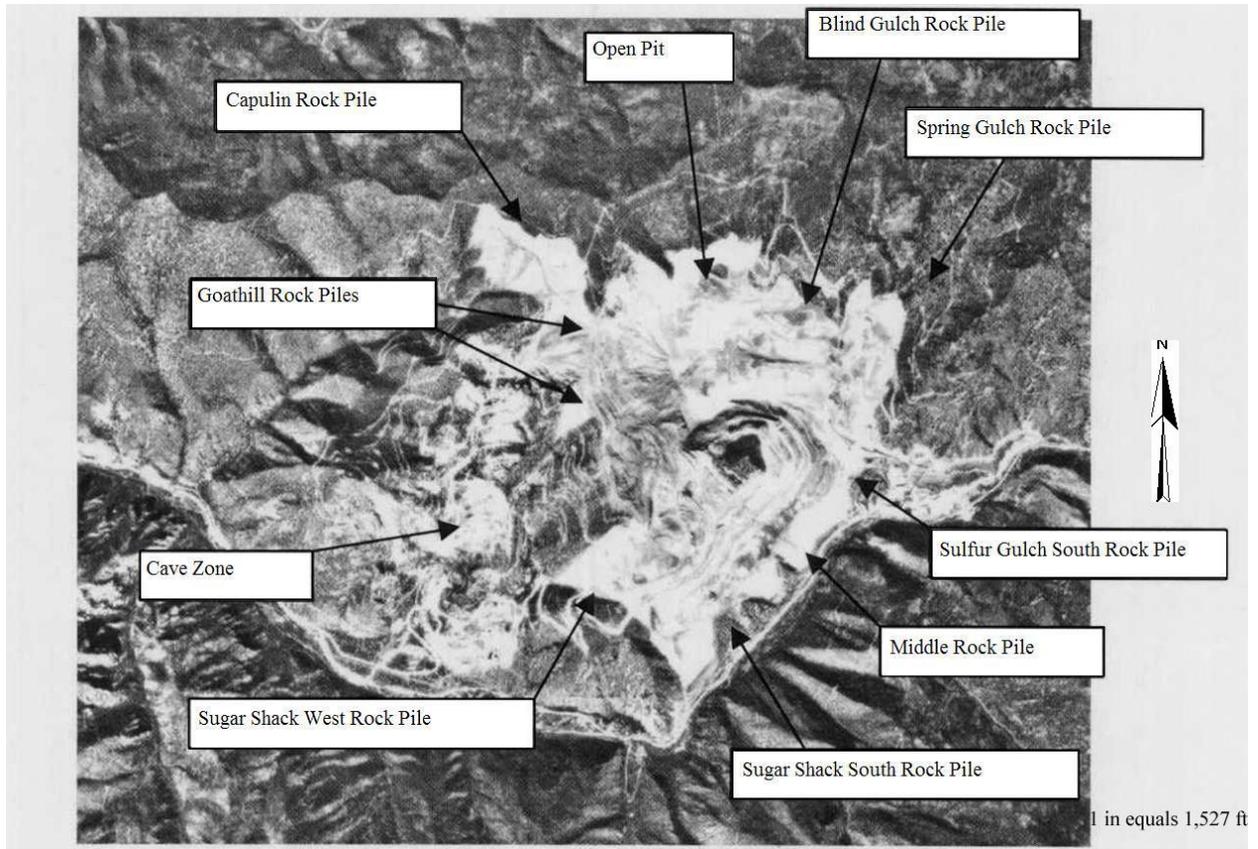


Figure 3. Aerial photograph of the Molycorp property.

Further to the west of and above the SGS survey area, drill hole WRD13 on the SGS rock pile was noted to vent continuously. The vapor was warm and humid. Subsequent gas analyses using a portable RKI Eagle gas analyzer indicated the vapor contained 20.9% O₂ and 0.32% CO₂ (measured on 2/2/05, V.T. McLemore, written communication, 4/29/05). We are currently monitoring this area. A similar analysis was done at the roadcut vent area, where steam venting contained 20.9% O₂ and 0.16% CO₂ (measured on 2/2/05). Ambient atmosphere contains 20.9% O₂ and 0.03% CO₂.

Goathill North (GHN) Rock Pile. Three areas were surveyed on the GHN rock pile. Each were on the slope rising above the road that cuts across the middle part of the rock pile and accesses drill hole SI-08 (Fig. 5). The surveys on this pile were conducted in May 2004 when there was no snow cover present. The first survey area was on the stable portion of the GHN rock pile, the second area was on the unstable portion, and the third survey area was a crack-like linear feature that transected the middle bench above the road. All of the locations were located above 2895 m in elevation.

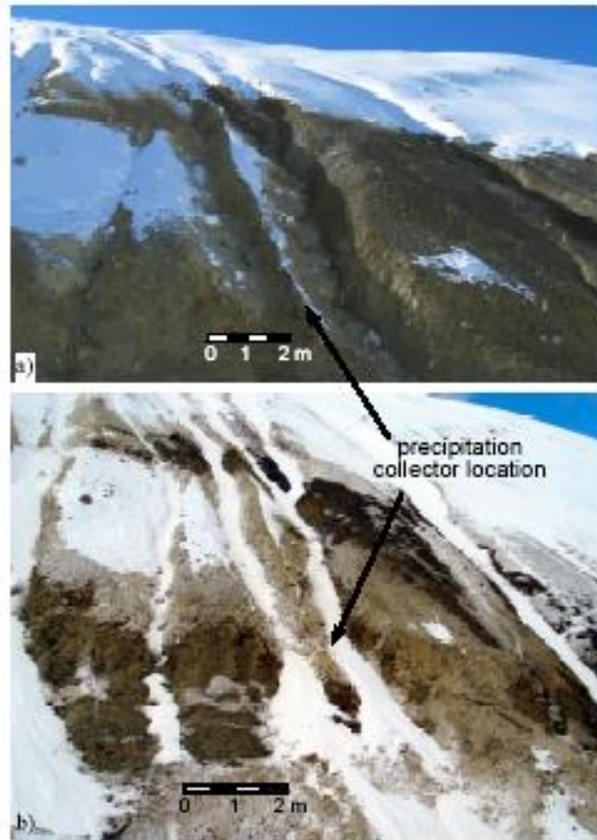


Figure 4. Changes in snow cover at the precipitation collector survey area on the Sulfur Gulch South rock pile, on 6 (a) and 8 (b) February 2004. The precipitation collector was installed on 7 February 2004. Snow was redistributed across the vicinity, presumably by wind, between the evening of the 7th and the morning of the 8th.



Figure 5. Access road cut across the Goathill North rock pile.

Field Methods

The thermal mapping was conducted using the FLIR SC 3000 thermal camera. The FLIR SC 3000 thermal camera uses a quantum well infrared photon detector to measure the temperature over the spectral range between 8-9 μm with a thermal sensitivity of 0.03 $^{\circ}\text{C}$ at +30 $^{\circ}\text{C}$. A handheld sensor was used to measure the ambient temperature and relative humidity. A standard operating procedure, SOP 51 (Molycorp Stability Project, 2004), was followed to set-up the thermal camera and to collect data. The thermal camera was placed on the tripod as shown in Fig. 6. When the thermal camera was horizontal, the distance to the slope surface was measured by tape and recorded into a field notebook. The appropriate ambient temperature, relative humidity, distance to the object, atmospheric temperature, and emissivity were entered in the camera software and recorded in the field notebook. The thermal images were collected in lateral sequences and saved.

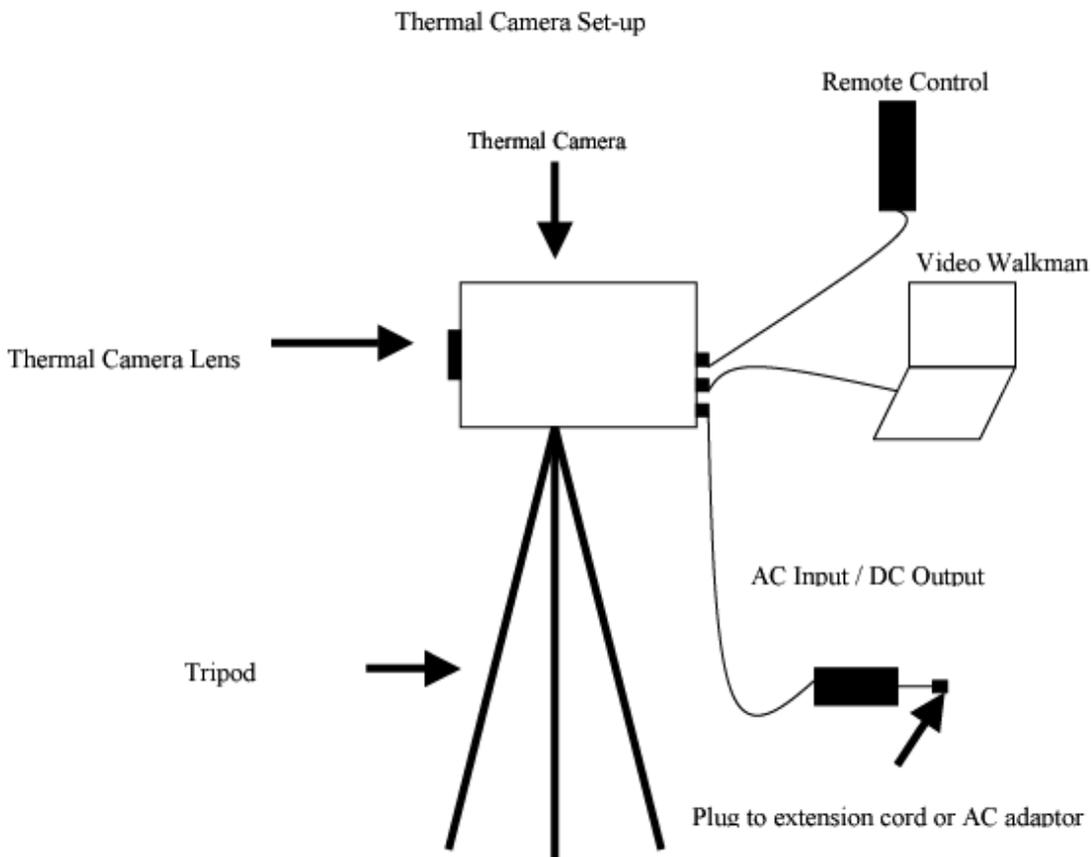


Figure 6. FLIR SC 3000 camera field set-up.

The thermal images were processed using the FLIR ThermaCAM Researcher 2000 software. The emissivity coefficient (ϵ) was assumed to be 0.95 for each of the surveys, because this is a typical value for soils (FLIR, 2000, Hudson, 1969).

In February, correlated series of thermal- and optical-wavelength images were collected at the SGS location using the FLIR SC 3000 thermal camera and a digital camera. The cameras were placed on a tripod and were used to collect a series of overlapping images, with no more than a 15-minute time lapse between the capture of the two different sequences. The sequences were captured from south to north.

In May, two series of thermal images were collected from north to south for the staked areas in the stable and unstable areas of the GHN rock pile. One series was collected with the thermal camera at a 0° tilt angle and the second series was collected with the camera tilted 15° upwards. The crack on GHN was depicted by using single images taken when the camera was tilted at angles of -15° , 0° , 15° , and 30° .

After processing, each temperature image was stored as a bitmap using a gray scale to represent the observed temperature range. The sequences of thermal and optical images from the February survey were joined into two separate composite images using Apple's QuickTime VR Studio. Thermal images collected in May for the Goathill North surveys were composited using Microsoft PowerPoint.

Results

Sulfur Gulch South Rock Pile

The results from the two surveys conducted on the Sulfur Gulch South rock pile show that the maximum temperature was 18°C in both February and May (Table 2 and Fig. 7). The maximum temperature in the February 2004 survey was greater than the ambient temperature, measured with a handheld sensor, of $2 - 3^\circ\text{C}$ on 8 February 2004 and $4 - 5^\circ\text{C}$ on 12 and 19 May 2004. The area containing the higher temperatures was roughly 40 m long by 40 m wide. The maximum temperature on the bare soil in February was also greater than the maximum temperature recorded for the snow-covered area or the background area represented by the portion of the rock pile approximately 20 m south of the bare area. The warmest regions were restricted to the bare areas in the images. However, the bare regions consisted of both relatively cold areas, ranging from -10°C to 2°C , and relatively warm areas, ranging between 12°C and 18°C (Figure 7). The warmest patches for the February survey were predominantly found on the slope faces.

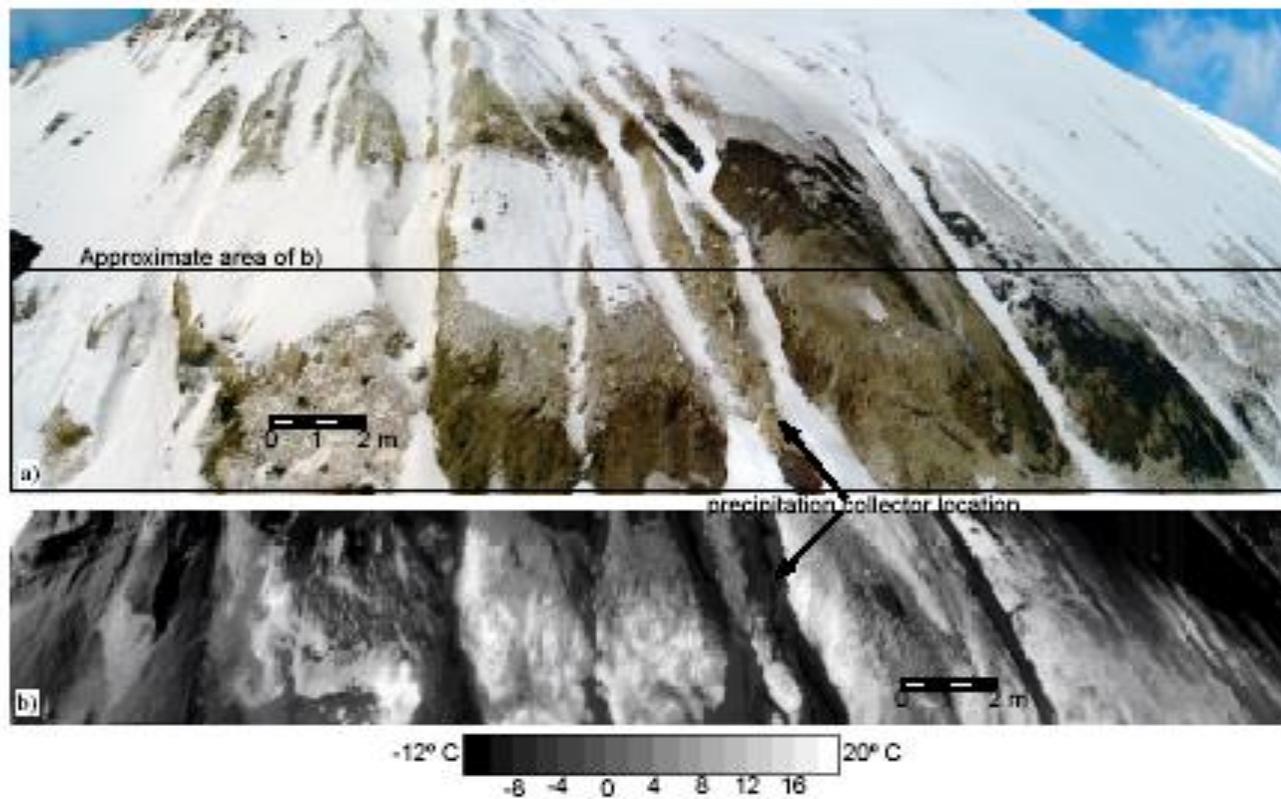


Figure 7. Optical and thermal composite pictures for the heat vent at Sulfur Gulch South rock pile on 8 February 2004. Composite a) is a panorama composed of separate optical photos taken with a digital camera. The thermal composite panorama (b) shows a gray-scale representation of temperatures.

Table 2: Minimum and maximum observed temperatures at SGS survey area

Date	Location	Minimum temperature (°C)	Maximum temperature (°C)
8 February 2004	Bare area	-10	18
	Snow-covered area	-10	2
	Background area	-10	2
19 May 2004	Entire survey area	5	18

Goathill North Rock Pile

Results from the three GHN survey locations indicate that temperature ranged between approximately 4 and 12° C (Table 3) in May 2004. The composite images of the stable and unstable portions of the GHN rock pile show a much smaller range in temperature than the SGS areas, but the differences appear to follow some spatial pattern (Fig. 8 and 9). Horizontal features have an arched appearance in the composite images due to the close distance between the camera and the surface of the rock pile.

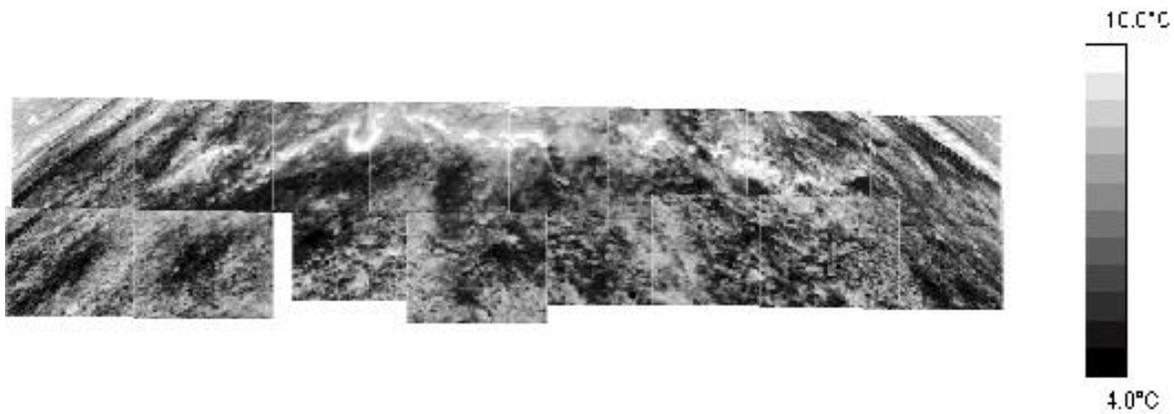


Figure 8. The composite thermal image of the stable portion of Goathill North Rock Pile was photographed in May 2004. The horizontal distance across this section is approximately 10.9 m and the vertical distance is approximately 2.36 m at the center.

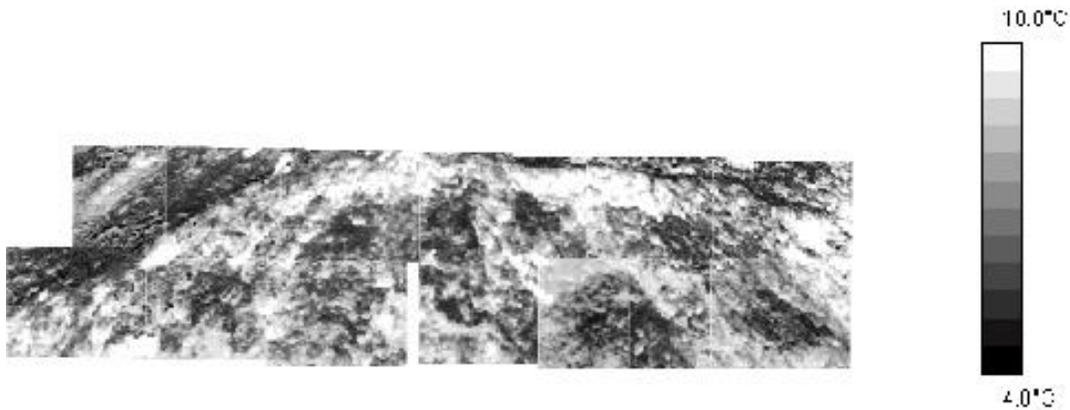


Figure 9. The composite thermal image of the unstable portion of Goathill North Rock Pile was photographed in May 2004. The horizontal distance across the widest portion of this section is approximately 9.2 m and the vertical distance across the tallest portion of this section is approximately 2.27 m.

Table 3: Temperature ranges across the GHN survey areas, 20 May 2004

Site Description	Maximum temperature	Minimum temperature
	(°C)	(°C)
Stable Portion (Unit C)	9.7	4.5
Unstable Portion (Unit D, E)	11	5.4
Crack	10.8	6.2
Excavated Crack	11.9	6.8
Dug Out	11.8	5.7

Discussion

The thermal camera showed the largest temperature differences in the SGS rock pile. The maximum temperature differences between the snow-covered patches and the bare regions was 16° C in February and 13° C in May (Table 2). These temperature differences are greater than the difference measured on GHN rock pile in May, which was only 6° C (Table 3).

By exhibiting a consistent maximum temperature of 18 °C in both February and May, the bare regions within the SGS survey area appeared to be venting heat, and therefore, the area is defined as a “heat vent” or a “hot spot”. If the maximum temperature from this heat vent continues to be relatively constant throughout the year, it would suggest that there is a steady heat flux from the interior of the rock pile to the surface. The most likely source of the steady heat flux is pyrite oxidation as there is no known geothermal activity in the rock underlying the SGS rock pile. The proximity of this heat vent to the venting drill hole, also on the SGS rock pile, suggests that they are both part of the same heat flow system.

The difference between surface and ambient temperatures at the GHN rock pile was much smaller than that observed at the SGS rock pile. The temperature difference could be explained by spatial variations in emissivity caused by local variations in rock thermal properties or by local variations in moisture content. Alternatively, heat could be venting from the interior of the GHN rock pile, but the flux is small compared to the energy added to the pile by solar radiation. Identifying the cause of the temperature differences would require determining whether there are emissivity variations caused by rock type or moisture content. Routine monitoring of surface and near-surface temperatures would show whether a specific region is venting heat at a low flux rate.

If the maximum temperature at the SGS heat vent remains significantly above the freezing point, infiltration could be locally enhanced within the heat vent area from snow melt. As mentioned above, we observed that snow was transported onto the heat vent from elsewhere on the rock pile, thus allowing the possibility for infiltration to exceed the amount of snowfall.

IR thermography could also be utilized to detect local variations in moisture content or fluxes of gases into or out of the rock pile. During the daylight hours when the short wave radiation from the sun is greatest, saturated zones will be cooler than unsaturated zones. The reverse is true in the early morning hours before dawn when solar radiation is absent. During this period, the saturated zones are warmer than unsaturated zones. Thus, the period before dawn is the most appropriate time to detect saturated zones as well as “hot spots”. Evaporative cooling from gas fluxes into or out of the rock pile or warm outflows such as at drill hole WRD13 can create local temperature variations that could be captured by thermal imaging. Locating and quantifying such gas fluxes could provide important clues about magnitude of pyrite oxidation as well as possibilities for controlling the oxidation.

Future work should include seasonal mapping of the heat vent areas on the rock piles when the ambient temperature is lowest (typically early morning hours) in order to capture the greatest temperature differences. In addition, the thermal camera could be used to detect variations in the thermal regimes of different layers within a rock pile.

Laboratory measurements of the emissivity coefficient of rock pile materials at different saturations should be made. If the variation in the emissivity (ϵ) at different saturations is significantly large, then moisture content samples should be collected from the materials being imaged to determine a relationship between water content and temperature.

Summary

Thermal imaging of two rock piles revealed that a heat vent at Sulfur Gulch South rock pile maintained the same maximum temperature of 18 °C in both February and May 2004 and showed that three areas of the Goathill North rock pile do not likely contain similar heat vents. If the heat flux at Sulfur Gulch South is shown to be steady, then it is likely that its heat is supplied by pyrite oxidation occurring within the rock pile. The thermal camera is a useful tool for quickly locating areas of possible pyrite oxidation and of gas fluxes in and out of a rock pile. This camera may be useful for investigations to locate the spatial distribution of water content and to define gas fluxes in various rock pile structures.

Acknowledgements

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