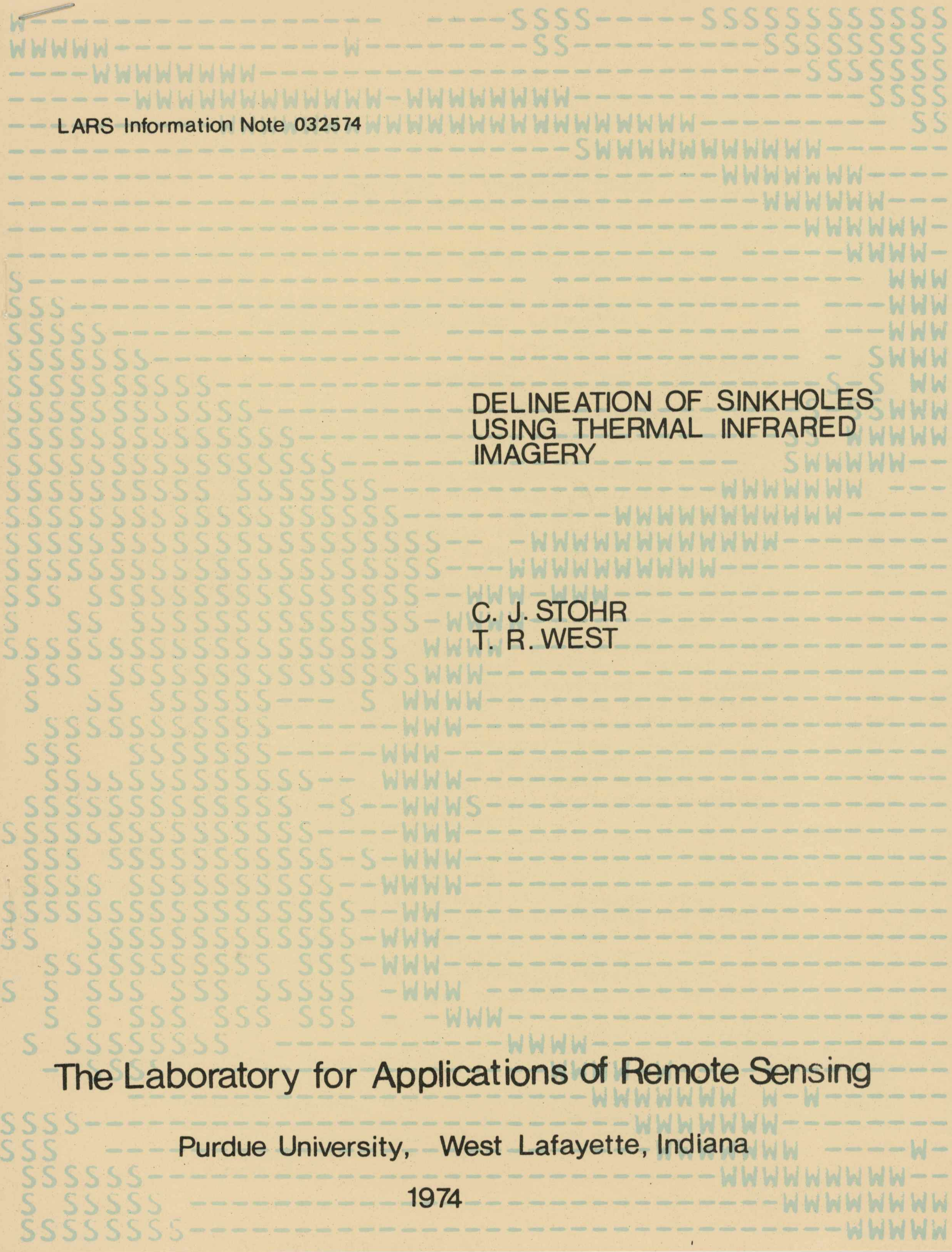

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DELINEATION OF SINKHOLES USING THERMAL INFRARED IMAGERY

C. J. STOHR
T. R. WEST

The Laboratory for Applications of Remote Sensing

Purdue University, West Lafayette, Indiana

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Abstract

Sinkholes, geologic hazards of concern in siting engineering works in carbonate terrain, are commonly detected through stereoscopic photointerpretation. Despite the complicated thermal response phenomena and resulting difficulty in image interpretation, some researchers have recently reported the feasibility of sinkhole location using thermal imagery (8-14μm) alone. A study was performed using multispectral data, flown spring and fall 1970 over a Staunton, Virginia test site. Reflective (.40 to 2.60μm) and thermal (4.5 to 13.5μm) data were collected at 2,000 and 5,000 foot altitudes. Sinkhole features were studied in two locations, a field of bare soil and one of grassy pasture. Manual interpretation of thermal imagery revealed that tones and patterns associated with sinkholes were repeated within their cover types and adjacent fields. Computer-aided analyses, nonsupervised (cluster) and supervised, were unable to delineate sinkholes within their cover types. Conclusion reached--thermal imagery analysis is best applied to supplement stereo photointerpretation.

Engineering geologists have relied on aerial photography as a primary tool for geological reconnaissance in the site selection of engineering structures. Location of geologic hazards has been a principal concern during this phase. A major hazard encountered in limestone terrains is the existance of caverns and sinkholes developed by solution activity. These features are usually

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identified through stereoscopic examination and interpretation of aerial photographs by location of surface depressions, disappearance of drainage and certain collapse features that suggest the presence of sinkholes.

Recently, location of sinkholes directly from and primarily by thermal infrared imagery in the 8 to 14μm wavelengths by manual interpretation (Noble, 1972 and Greene, et al. 1970) or computer-assisted analysis (Coker, et al., 1969) have been reported in the literature. The authors of this paper, however, question the direct application of thermal infrared imagery in sinkhole location because of theoretical and empirical considerations.

Theoretical Considerations

The response recorded in the thermal infrared region between 3 and 16 micrometers is explained by the Stefan-Boltzman Law, the integration of Planck's equation over all wavelengths. For natural materials (graybodies) this equation is:

$$W = \varepsilon \sigma T^4$$

where

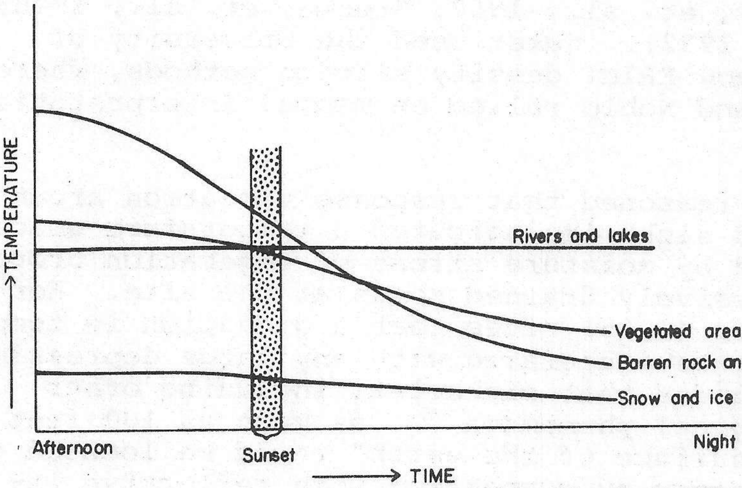
W is the total radiant emittance
σ is the Stefan-Boltzman constant, 5.67×10^{-12} $w\ cm^{-2}\ (°K)^{-4}$
ε is the emissivity of the target (for a natural substance, graybody, $\varepsilon<1$)
T is the absolute temperature, °K

The emissivity of a substance is an intrinsic property. Because pure substances rarely occur in nature, the net effects of a combination of substances comprising the target yield an overall emissivity which must be considered in the interpretation of thermal infrared imagery. However, it is difficult to assess variation in emissivity for cover types over a flightline, so that commonly the emissivity of basic cover types is assumed as unity in routine investigations.

Most researchers agree that diurnal changes in temperature have a primary effect on thermal response. A variation of .1°C yields an energy difference of 6.12 x 10^{-6} watts/cm^2, an amount easily detected by a radiometer (Smith, 1969). The effects of diurnal temperature changes for basic cover types are summarized in Figure 1. Interpretation of thermal imagery depends a great deal on the time of day the imagery was recorded and the behavior of the cover types under the microclimatological conditions at the time of flight.

The effects of the atmosphere on the recorded response are numerous and are difficult to assess. Atmospheric effects are due primarily to absorption and emittance of gases in the air column between the sensor and the target, and to microclimatological phenomena at the earth-air interface. The absorption of carbon dioxide, nitrous oxide, ozone and water vapor are dependent on the local pressure and temperature. The measurement of the total air column is neither practical nor desirable, and for most interpretation these effects are considered uniform over a flightline.

The effects of microclimatological phenomena can be measured more readily than those for absorption. Microclimatological phenomena such as



After Smedes, 1968

Figure 1. Diagrammatic curves showing rates of cooling for different cover types, and reversal of relative intensities from day to night.

evaporation and insulation are difficult to assess from thermal imagery, but heat exchange between soil and air may be detectible in extreme cases such as wind streaks (Geiger, 1965). Other considerations caused by aircraft motion, electronic noise, weather and processing are described by Sabins (1973).

Thus meaningful interpretation of thermal infrared imagery is difficult because of the numerous, complex interactions between cover type properties and environment, and their overall effect on the total radiant emittance. The lack of predictability over the range of cover types and environmental conditions found in a flightline precludes the use of thermal imagery for routine application to engineering investigations (Parker, 1968). Consequently many researchers consider thermal imagery to be a supplementary tool providing information not available from aerial photography and other sources.

Despite the complicated nature of thermal response phenomena and the difficulty in making meaningful interpretation of thermal imagery, some researchers after only a limited consideration of these complications perform detailed evaluations for sinkhole location using the 8 to 14μm wavelength band (Coker, et. al., 1969; Greene, et. al., 1970; and Noble, 1972). Coker used the University of Michigan (now ERIM) density slicing methods, whereas Greene and Noble relied on manual interpretation techniques.

Coker reasoned that response variation around an observed sinkhole indicated a temperature gradation caused by moisture stress of vegetation brought on by excessively drained soils at the site. However, Geiger (1965) cites that a gradation in temperature may be associated with any large depression. Coker concluded that sinkholes, including other hydrogeological phenomena "...as much as 100 feet below the surface of the earth" could be located on thermal imagery by comparison with reflective infrared imagery. This was based on the location of sinkholes within a relatively confined area as contrasted to an extensive flightline.

Noble (1972) undoubtedly was strongly influenced in his manual interpretation of thermal imagery in Virginia by his detailed knowledge of the sinkholes and their field locations. Consequently, objectivity under such circumstances would be difficult if not impossible in manual interpretation. A more objective approach would entail location of sinkholes in unfamiliar terrain using the imagery and then confirming their presence by field examination.

A recent study by Smith (1973) in southeast Missouri using thermal infrared imagery and side-looking radar (SLAR) imagery presented conflicting results relative to previous work. Smith concluded that thermal imagery was of little or no use in locating sinkholes in cultivated or pastured areas, and was of no use in locating sinkholes in forested areas.

Based on the information above and on the following study the writers conclude that sinkholes cannot be delineated solely by interpretation of thermal infrared imagery.

Empirical Study

Multisensor data were collected over a test area near Staunton in August County, Virginia during the spring and fall of 1970 (see Figure 2). The flights were planned jointly by the Virginia

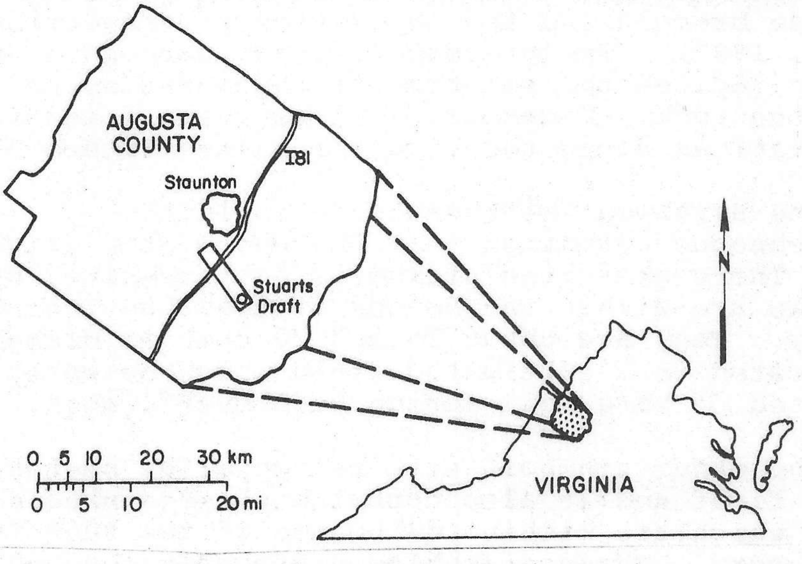


Figure 2. Location of test area in Augusta County, Virginia.

Highway Research Council and the U.S. Department of Transportation, Federal Highway Administration to maximize the effects of moisture contrast without the obscuring effects of snow cover or deciduous foliage. Daytime and nighttime data were collected by the University of Michigan multispectral scanner on 5000 and 2000 foot missions on April 7 and 8 and on December 14 and 15. Reflectance (.4 to 2.60μm) and thermal data (4.5 to 5.5μm and 8.0 to 13.5μm) were collected between 1100 hours and 1200 hours in order to achieve maximum sunlight with minimum shadows, and minimum cloud cover. Nighttime thermal (4.5 to 13.5μm) missions were made between 2300 hours and 0200 hours to achieve an equilibrium condition where only emitted radiation from the environment would be recorded.

In addition, 9 inch by 9 inch color and color infrared photography of the spring flight provided additional information. Cathode ray tube (CRT) imagery was supplied with the April flights in the reflective and thermal infrared wavelength bands.

Geology

The flightline is located in the Valley and Ridge Province in a region with characteristic karst development. Present solution activity in the study area includes calcareous cementation of collapse breccia and the deposition of travertine (Rader, 1967). The presence of this carbonate deposition implies the solution of the surrounding limestone rock. Sinkholes (dolines) are found in two locations along the flightline (see Figure 3).

The northwest sinkhole site is in the Conococheague Formation near the end of the flightline. There are three sinkholes at this site, but only two are within the bounds of the 2000 foot MSS imagery. They are about 25 and 20 feet in diameter and located in a cultivated field which essentially consisted of bare soil during both overflights.

The other sinkhole site is two miles southeast of the first and it also contains three sinkholes two of which are within the bounds of the 2000-foot MSS imagery. These sinkholes are roughly 60 and 80 feet in maximum diameter and situated in a grassy

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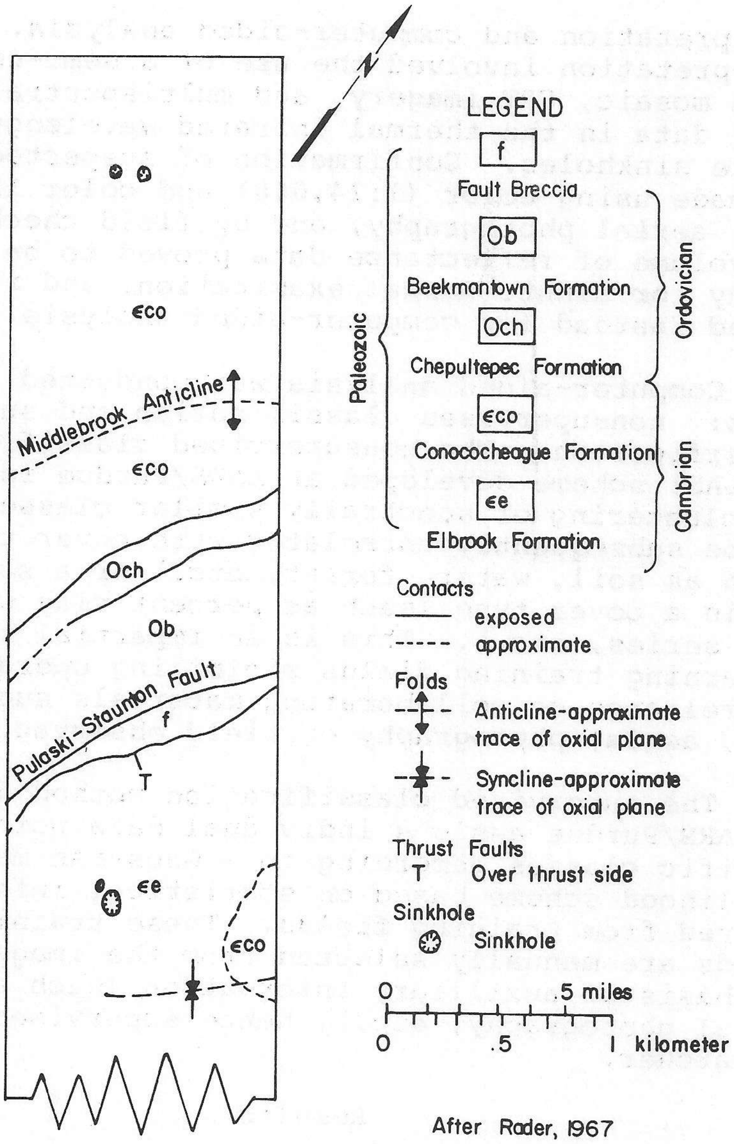

After Rader, 1967

Figure 3. Geologic map of the northwest portion of the Stuarts Draft test area showing the two sinkhole sites.

pasture. Two other areas in the pasture are suspected to be paleokarst or collapsed sinkhole features. At neither location did the sinkholes pond water.

Procedure

Two approaches were used in the study of sinkhole location from thermal infrared imagery: manual interpretation and computer-aided analysis. Manual interpretation involved the use of a semi-controlled photo mosaic, CRT imagery, and multispectral scanner (MSS) data in the thermal infrared wavelengths to locate sinkholes. Confirmation of suspected sites was made using color (1:24,000) and color IR (1:9600) aerial photography, and by field checking. The volume of reflectance data proved to be too unwieldy for minute manual examination, and it was reserved instead for computer-aided analysis.

Computer-aided analysis was conducted in two parts: nonsupervised classification and supervised classification. The nonsupervised classification (NSCLAS) scheme developed at LARS/Purdue involves the clustering of spectrally similar classes which may be subsequently correlated with cover types (such as soil, water, forest, etc.) or a subclass within a cover type (such as percent clay within a soil series, etc.). This is an impartial method of discerning training fields minimizing operator bias and reliance on collaborating materials such as maps, aerial photography or field observations.

The supervised classification method developed at LARS/Purdue assigns individual data points to specific classes according to a Gaussian maximum likelihood scheme based on statistical information derived from training fields. These training fields are manually selected from the imagery on the basis of auxilliary information (such as maps, aerial photography, etc.), hence supervised by the researcher.

Results

Manual interpretation of reflectance and emissive data revealed several points of interest. Most significant was the inability to locate sinkholes using thermal infrared when applied as the sole means. Anomalies associated with sinkholes could be distinguished from basic cover types in which sinkholes were found (pasture and bare soil) only by stereoscopic examination of aerial photographs and location of the features in the imagery relative to landmarks and field boundaries.

Figure 4 shows night thermal IR imagery at the northwest sinkhole site collected at 2000 feet.

DELINEATION OF SINKHOLES

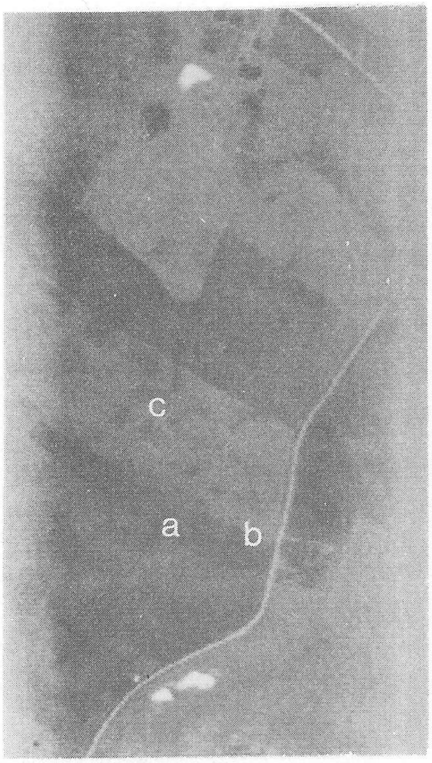

Figure 4. Thermal infrared imagery (8.0-13.5μm) of the northwest sinkhole site.

Imagery taken at the two thousand foot altitude was found more useful for interpretation than the 500 5000-foot data. In this figure sinkholes are located in a plowed field which is characterized by high moisture areas seen as dark circular tones on the imagery. Dark tones at a and b are sinkholes but appear much the same as the nearby areas of higher moisture content. These tones are also repeated throughout area c which is not a sinkhole area.

The southeast sinkhole site, a grassy pasture, is shown in Figure 5. Figure 5 A and B show a comparison between the nighttime and daytime infrared imagery. Numerous light tones in the daytime imagery correspond with the dark areas in the nighttime imagery. Only two of these anomalies are associated with sinkholes, a and b. Aerial photography is needed to differentiate between these sinkholes and those depressions not associated with sinkholes. At both sites there is no distinctive tone or pattern that can lead an interpreter to conclude that one feature is a sinkhole and another is a simple depression or other terrain feature on the basis of the thermal infrared imagery.

Nonsupervised classification of both sinkhole sites, examined in a range from 20 to 4 cluster classes, did not yield a spectrally separable class for the sinkholes using either the reflective or emissive data. Although a gradation in temperature for the sinkholes is detectible on the cluster maps of thermal imagery, this phenomenon is not unique to this landform. Figure 6 shows the northwest

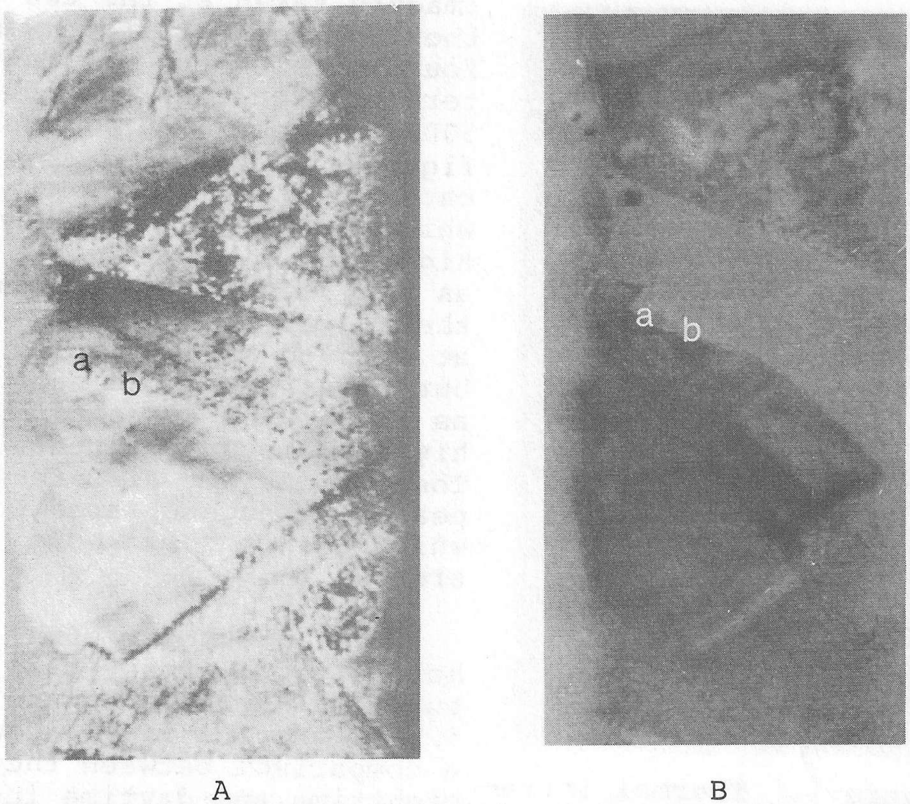

Figure 5. Comparison of daytime and nighttime thermal infrared imagery (8.0 to 13.5μm) of the southeast sinkhole site.

sinkhole site where identical spectrally separable classes are assigned to sinkholes and to other higher moisture areas.

Supervised classification of thermal imagery did not enhance the data, and in most cases tended to degrade it. The supervised classification of the reflective data distinguished many cover types but failed to delineate sinkholes within the cover type containing them.

Computer-aided sinkhole location using reflective or emissive data, or manual interpretation of thermal IR imagery as a sole means of sinkhole location is improbable at this time because of the complex nature of emissive radiation and the parameters affecting thermal response. However, analysis of thermal imagery in conjunction with stereo-

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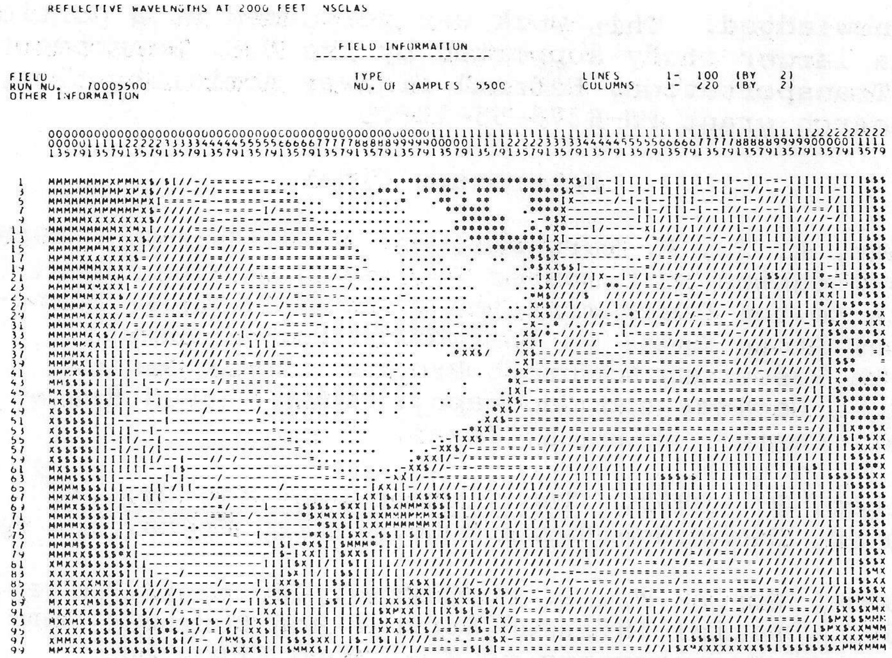

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REFLECTIVE WAVELENGTHS AT 2000 FEET  NSCLAS

                         FIELD INFORMATION
                         -----------------

FIELD                          TYPE                          LINES     1-  100  (BY   2)
RUN NO.    70005500            NO. OF SAMPLES  5500          COLUMNS   1-  220  (BY   2)
OTHER INFORMATION
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Figure 6. Cluster map of the northwest sinkhole site using ten cluster classes. Reflectance decreases with visual density of the characters.

scopic examination of aerial photography may be used as a supplementary tool.

A proposed method for sinkhole location in carbonate terrain is as follows:

1. Locate topographic depressions using stereoscopic interpretation
2. Delineate circular anomalies on thermal infrared imagery
3. Field check each area where both conditions 1 and 2 prevail.

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