Locating Subsurface Gravel with Thermal Imagery: Preliminary Results

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The subject of this paper is the correlation of thermal imagery with subsurface gravel deposits in vegetated areas where some ground surface is exposed. Geologic history was reviewed to select potential areas of study. An overflight was made using a thermal multispectral scanner. The data are processed with a computerized system to delineate areas showing a quartz spectral signature radiated from the ground surface. These areas were then compared with exploratory drill-hole data and found to correlate in every location where drilling had located substantial subsurface gravel. The correlation was noted during a search for gravel on national forest land in Louisiana. Processed data from an airborne scanner were compared with exploratory drill-hole logs. The correlation was noted at eight widely dispersed locations of subsurface gravel deposits. Areas without subsurface gravel showed negative correlation. It was concluded that more time and effort are needed to verify the usefulness of the correlation for locating new gravel pits.

The need for identifying and developing local sources of native road-surfacing materials for timber-haul roads has been determined by the Forest Service, U.S. Department of Agriculture (USDA), Southern Region and by the USDA Forest Service Washington Office. In the Southern Region, pits operated by the Forest Service are rare because of the high frequency of commercial aggregate pits over most of the region. A review of available geologic data has enabled the identification of areas most likely to contain usable materials. However, these areas are still too large in extent and too variable in rock content to allow cost-effective location of prospective aggregate pits.

Ample evidence attests to the extensive Pleistocene gravel deposits in the Kisatchie National Forest in Louisiana. These deposits vary in age from 800,000 to 80,000 years *(1)*. In the late 1930s units containing the gravels were mapped by Fisk *(2)*. Since that time, several large commercial gravel pits have been developed adjacent to and on national forest land under permit. This gravel was noted to be of chert origin *(2)*. Chert is a sedimentary rock consisting of a cryptocrystalline variety of quartz and amorphous silica *(3)*. A number of existing pits are in operation or have been exhausted, and continuing exploration by Forest Service engineering personnel and private operators under permit using exploratory drilling equipment has located other deposits. During the period 1982 to 1985, the Forest Service drilled more than 1,000 exploratory holes on the Kisatchie National Forest in search of gravel. This effort resulted in discovery of eight sites with a high potential for pit development and several others showing modest deposits. Commercial prospecting during that same period has yielded five sites. In spite of this effort, many square miles of the Kisatchie National Forest remain unexplored because of poor access and lack of information about likely sources. Although this tedious and often expensive trial-and-error drilling has had its intermittent successes, it is not a satisfactory method for long-range gravel resource management. Thus to obtain an improved overall understanding of the extent of gravel reserves, an investigation of the use of remote sensing was begun several years ago.

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Attempts to use visible infrared and natural color aerial photography to identify subsurface gravel deposits failed completely. Publication of pertinent information *(4)* provided the inspiration for trial use of thermal imagery. In 1982 a study on the Kisatchie National Forest in Louisiana was proposed and discussions with the Earth Resources Laboratory (ERL) of the National Aeronautics and Space Administration at the National Space Technology Laboratory (Bay St. Louis, Mississippi) led to the initial acquisition of data, followed by several attempts at processing the data and correlating the obtained images with drill-hole data. The rationale and details of the effort are given in the following paragraphs.

EQUIPMENT

The thermal infrared multispectral scanner (TIMS) was developed by ERL as a definition tool for future satellite-borne, geology-oriented sensors. First flights for the completed instrument were made in summer of 1982 *(5)*. TIMS is an electro-optical line scanner currently operating in the airborne mode, sensing in six narrow bands in the range of 8.2 to 12.2 μm:

Band	*Spectral Coverage (μm)*
1	8.2-8.6
2	8.6-9.0
3	9.0-9.4
4	9.4-10.2
5	10.2-11.2
6	11.2-12.2

Average spectral sensitivity is approximately 0.1°C *(5)*. The higher sensitivity and multispectral capability of TIMS permit the detection of phenomena not detectable by commercially available devices. The sensor is flown in a Lear 23 aircraft. Instantaneous field of view (IFOV) and lateral coverage of flight lines are dependent on aircraft altitude. Within the operational limits of the Lear 23, between 2000 and 12 000 m, the altitude above terrain may be varied to provide an IFOV ranging from 5 to 30 m. For mapping aggregate deposits, an altitude of 12 000 m above the terrain provides data with 30-m pixels and a swath width of approximately 18.7 km.

DATA ACQUISITION

To acquire TIMS data for a specific location, a map of the proposed area with boundaries delineated is presented to ERL. Following a brief study, ERL provides a cost estimate and time periods available for the flight. The estimated cost must be funded before data acquisition from concurrent fiscal year funding. The use of TIMS is available only to government agencies. The actual flying time depends on weather as well as prior schedules. A 10-day period of no precipitation before the flight is necessary to prevent interference of surface moisture, and the air must be free of clouds or fog during operation of TIMS. Coordination between ERL and a ground station near the site is essential to a successful effort.

DATA PROCESSING SYSTEM

The Resource Evaluation and Monitoring Integrated Analysis System (REMIDAS) is a minicomputer-based system implemented by the Forest Pest Management (FPM) unit of the USDA Forest Service Southern Region in cooperation with the Georgia Institute of Technology Engineering Experiment Station (EES). The REMIDAS facility is located within the offices of the FPM Aerial Survey Team at the Southern Region, Doraville, Field Office. REMIDAS is designed to permit the compatible analysis of digital scanner data from collateral data such as soils and terrain. The components of the system are as follows:

1. Data General S250 integral array processor;
2. Ramtek high-resolution color display;
3. Two 1,600-byte-per-inch (bpi) tape drives;
4. Disk storage, 200-megabyte;
5. Digitized station (for input);
6. Electrostatic plotter (for output), 22 in.; and
7. Graphic camera (for output).

The current REMIDAS software was developed by EES. The bulk of this software supports the image-processing functions necessary for the display, rectification, classification, and enhancement of digital imagery. Digitizing and geographic data base capabilities are provided primarily for the integration of collateral data and to provide output compatible with user systems.

DATA PROCESSING PROCEDURES

Following acquisition, the high-density tape recorded on the aircraft is preprocessed by ERL. Computer-compatible tapes (1,600 bpi) in the standard ELAS band interleaved by line were provided to the Forest Service. This requires about a week. Once the data have been loaded into the REMIDAS system, density stretching by histogram equalization and level slicing are used for initial evaluation. The data are registered to map coordinates based on a linear transformation using the pixel coordinates of a series of readily identifiable points and nearest neighborhood resampling. Road intersections, often used as control points in registering satellite data in the visible and reflected infrared range, are more difficult to locate on thermal imagery. An enhancement procedure to separate road alignments from the remainder of the scene was developed by the authors and used to improve the location of road intersection control points.

PROPERTIES OF THERMAL IMAGES

Thermal imaging, with scanners in the thermal infrared band (8 to 13 μm), has been used successfully to identify sought-after subsurface materials with a thermal inertia substantially different from that of adjacent materials (*6*,pp.257–274). Examples are the delineation of boundaries between crystalline rocks and sedimentary rocks and the study of volcanoes (*7*,pp.275–296).

The apparent surface temperature is affected by the type of underlying material, providing an indicator of variation in subsurface materials across the landscape. This is because there is a substantial difference in thermal inertia between materials of different composition, for example, road-surfacing materials and the unusable materials generally found in association with them. High thermal inertia indicates a capacity for retaining heat. The ratio of thermal inertias of two adjacent materials provides a measure of the contrast to be expected in their thermal images. High ratios will result in greater contrast. Typical thermal inertia ratios (*6*) for dry materials of interest in road construction and surfacing are as follows:

Material	*Ratio*
Sandy gravel and sandy clay	2.0
Sandstone and shale	1.6
Granite and sandy soil	2.2
Granite and moist clay soil	1.2

The thermal inertia ratio diminishes with increasing soil moisture content because the high latent heat capacity of soil moisture can completely mask buried rock. Soil moisture can most easily be avoided during relatively dry fall weather following maximum summer heat penetration. Because the annual heating wave penetrates to depths of 20 m compared with 1.5 m for the diurnal wave, fall dates also provide periods of maximum thermal contrast between materials of different thermal inertia.

The spectral signatures of a variety of rock and clay minerals have been identified in the literature (*8*,pp.5–46). The 8- to 14-μm region is of particular interest because of the intense silicon-oxygen molecular band-stretching modes that occur and because of the minimum atmospheric absorption. The maximum silicon-oxygen stretching in quartz occurs in the 9- to 9.4-μm region, which coincides with TIMS Band 3 and results in notably low transmission on this band. This stretching also results in a moderate transmission at 8 μm (TIMS Band 1) and high transmission at 12 μm (TIMS Band 6). Other minerals have peaks and dips at different locations on the spectrum and thus can be differentiated from quartz. Figure 1 shows examples of the spectral signatures of quartz and other minerals (*8*).

In contrast to minerals, vegetation produces a nearly flat spectral signature in the thermal range, completely masking any mineral signature hidden by vegetation (*9*,pp.364–380).

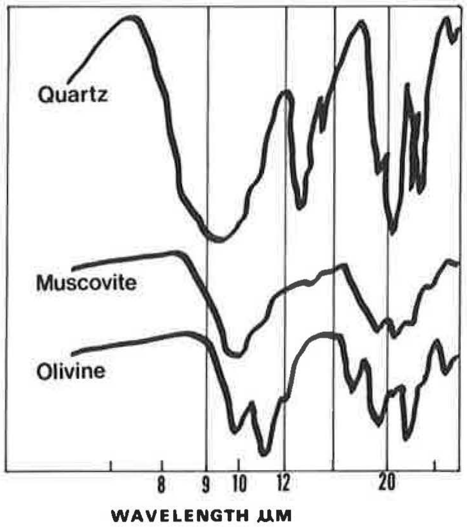


FIGURE 1 Spectral signatures of minerals.

Patches of surface soil among the vegetation must be visible from the air if the soil heat is to be recorded by TIMS.

INFLUENCE OF GEOLOGY AND VEGETATION

Thermal energy from the sun warms the earth's surface during the hot summer months. The heat flows downward toward cooler regions. Subsurface sandy gravel deposits have a higher conductivity and a lower heat capacity than overlying sands and sandy clays. These gravel deposits draw heat from the overlying materials.

By early fall when air temperatures are dropping and surface materials are losing their summer heat, the thermal conduction from these warmed gravel deposits is reaching a maximum. During the early morning hours when surface temperatures are low, heat from the warmer gravel, which consists mainly of quartz, flows upward toward the surface through the sands and clays. Thus when the radiation from the quartz layers surfaces through overlying layers of sand and is detected by the thermal sensors, it provides higher apparent temperatures than do adjacent areas without subsurface gravels. Figure 2 shows how a subsurface gravel deposit affects the surface temperature.

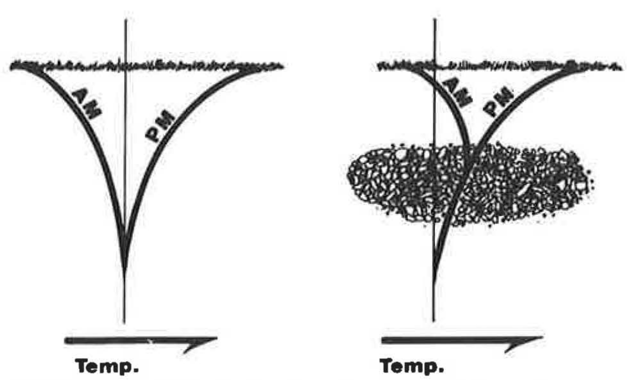


FIGURE 2 Effect of subsurface gravel deposits on surface temperature.

Because of local variations in surface temperature caused by vegetation and soil moisture, these differences in apparent temperature caused by subsurface gravels are not sufficient by themselves to identify a deposit. Geomorphic processes provide additional data required for detection. Gravels are laid down on steeper gradients than are fine-grained sediments. Over the broad areas necessary for detection by TIMS at 30-m resolution, these steeper gradients are maintained in the overburden as it is formed by deposition of finer-grained material. This results in a high velocity of flow for surface water, which carries the silt particles away and leaves a predominance of sands in contrast to the silts found on flatter adjacent areas. Thus the surface material overlying the gravel deposits has a high percentage of coarse-particled quartz sand (Figure 3).

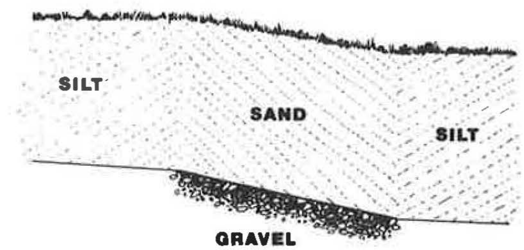


FIGURE 3 Ground slope effects.

The natural processes of silica diagenesis have the potential for enlarging the mineral grain size in surficial sands overlying chert gravel deposits. During the spring and early summer, when the water table is at the ground surface, evaporation can cause an upward flow of groundwater, bringing dissolved silica from the slightly soluble buried chert deposits and depositing opal silica overgrowths on the quartz sand crystals at the ground surface, which gradually increases their size *(10)*. Chert has a solubility that is 2 to 3 times that of igneous quartz *(10)*. Opal silica radiates a thermal signature similar to that of quartz *(8)*. Feder has discussed a similar phenomenon in which methane gas leaking from subsurface hydrocarbons caused ground surface alterations in vegetation and minerals that could be detected with thermal imagery, revealing the presence of the subsurface deposit *(11)*.

The finer-grained quartz in the silt range does not have an easily recognized spectral signature, in contrast to the sand- and gravel-sized quartz particles, which provide a pronounced spectral signature in the range covered by TIMS. Although much of the Southeast is vegetated, grass and tree cover is not continuous during the dry late summer, and frequent patches of unvegetated ground surface are visible from the air.

DATA ANALYSIS

For quartz deposits, the authors found that when Bands 6, 3, and 1 are displayed simultaneously in the red, green, and blue channels, respectively, on the REMIDAS color monitor, the surficial gravel deposits bare of vegetation show in red, and buried gravel deposits are in darker magenta because of the low reading in Band 3. However, not all dark areas are due to quartz, because certain ground conditions result in cooler tem-

peratures. To locate the quartz deposits, the spectral signature for each 30-m pixel must be inspected by reading and comparing the digital data from each of the three bands. REMIDAS software provides the capability of displaying the digital values of the three bands simultaneously on the monitor as the cursor is moved from pixel to pixel using a joystick.

To reduce the time requirements for pixel processing and to ensure that no critical pixels were missing, the authors developed a set of decision rules for detecting gravel deposits and separating buried from surficial deposits by comparing exploratory drill-hole data with the TIMS digital data. The authors noted that although areas containing surficial or shallow gravel deposits show an exaggerated quartz spectral signature, areas with deeper deposits show a more subdued signature.

For quartz identification, Bands 1, 3, and 6 are used in the decision process. In Figure 4 these bands (hatched areas) are shown superimposed on the quartz spectral signature. Signatures developed from TIMS data are shown in Figure 5 for several ground conditions. The final classification is obtained by level slicing the ratio of the differences between Bands 1 and 3 and Bands 3 and 6. To be considered for final classification, a pixel must meet three criteria. These criteria were selected by comparing the digital data with the drill-hole data from the same area.

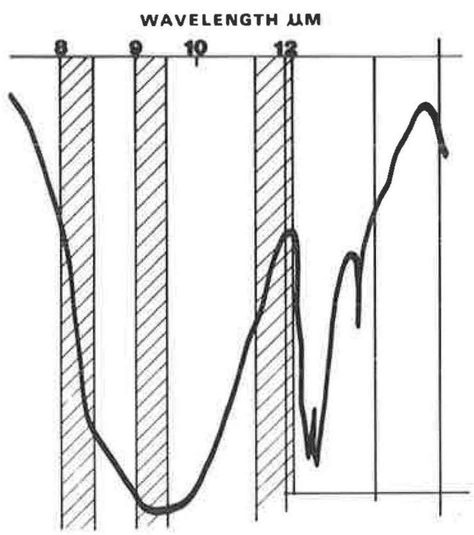
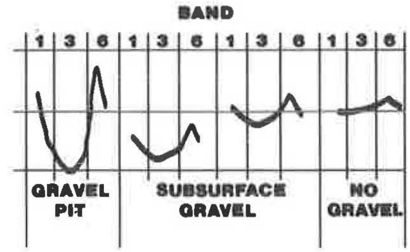


FIGURE 4 TIMS Bands 1, 3, and 6 superimposed on quartz spectral signature.

1. The digital count in Band 1 must be 4 or more counts higher than the count in Band 3. Drill-hole data examined from areas with less than this difference show only sand.
2. The digital count in Band 6 must be 9 or more counts higher than the count in Band 3. This difference was typical of areas containing gravel deposits.
3. The ratio (6 – 3)/(1 – 3) must be 2 or higher as noted in all areas containing gravel deposits. Following further field study, this ratio was separated into ranges of 2.0 to 2.5, 26 to 3.0, 3.1 to 3.5, and greater than 3.5 to differentiate between the trace deposits of less than 30 cm and thicker, exploitable gravel deposits.



1. BAND 1 - BAND 3 > 3
2. BAND 6 - BAND 3 > 8
3. $\frac{\text{BAND 6 - BAND 3}}{\text{BAND 1 - BAND 3}}$ > 2.0, 2.5, 3.0, 3.5

FIGURE 5 Spectral signatures developed from TIMS data.

These criteria, summarized in Figure 5, were developed for a particular climate, location, and mineral and will differ in other situations.

INITIAL DEVELOPMENT PROJECT

An overflight by ERL using TIMS was programmed for October 1983 for the Kisatchie National Forest in Louisiana. The October date was chosen because at this time of the year, the earth has already soaked up the maximum solar heat for the year and surficial material is beginning to cool. The flight was made in the early morning hours between 2:00 and 4:00 a.m. to get maximum cooling of surface and maximum contrast with warm subsurface gravel deposits. A 10-day period without precipitation before the flight was noted by coordinating Forest Service personnel in the site vicinity. The October 1983 flight with TIMS was successful and usable imagery was obtained.

Following display and data analysis, areas in the imagery showing a quartz spectral signature were compared with exploratory drill-hole data and with locations of existing developed gravel pits. In every comparison (eight widely dispersed sites), locations of known deposits showed a quartz signature; surficial or shallow deposits showed the stronger signature and deeper deposits showed a more subdued signa-

FIGURE 6 Location of study area.

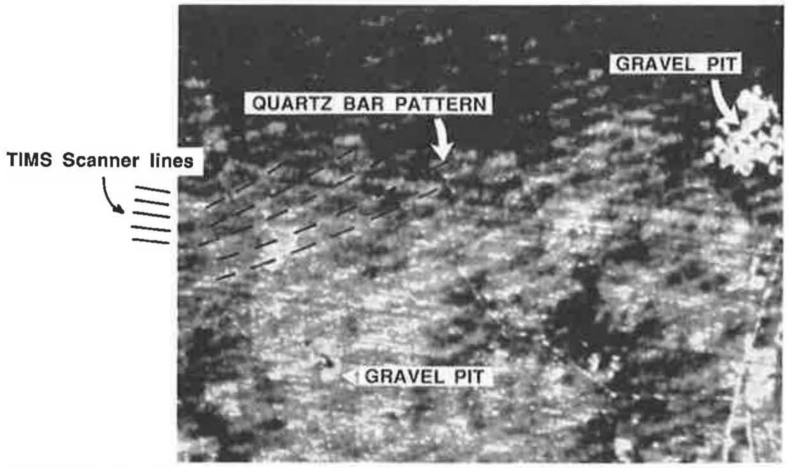


FIGURE 7 Processed thermal image scene, Evangeline District, Kisatchie National Forest.

ture. In no case did an explored area without gravel show a quartz signature of similar magnitude to that for the graveled areas. In those explored areas with very weak quartz signatures (i.e., Band 1 – Band 3 = 3 or less), the drill holes showed only sand.

The data selection criteria discussed previously were then used to code all pixels meeting the requirements for a quartz signature in a scene on the south end of the Evangeline District of the Kisatchie National Forest (Figure 6). These pixels were displayed in separate colors on the scene to show the locations of the areas emitting quartz signatures of each magnitude (Figure 7). In Figure 7 signatures of higher magnitudes are brighter shades of gray. This scene is the maximum that can be processed with currently available software.

GROUND VERIFICATION

In the initial study of the south end of the Evangeline District, the quartz spectral signature delineated a series of quartz bars running 30 degrees north of east across an area 7 mi wide (Figure 7). About 16 bars are discernible in the scene over a reach of 3 mi. Because these bars parallel the Pleistocene shoreline identified in the Louisiana geologic reports *(2)*, it is assumed that they were formed as the surf washed fines from the sand and gravel mixture and that successive bars formed as the ocean receded during the last period of glaciation. An extensive effort to correlate the images with vegetation, topography, water table, or system noise was made, but without success.

During 5 days of drilling allotted to verifying the thermal image developed in this scene, it was possible to drill at several isolated locations from the northeast corner of the scene to the west side and to drill a number of holes at a single location on the west side of the scene where a heavy concentration of quartz was indicated. Drilling sites were selected where existing roads intersected the bars of quartz signature or, for negative verification, where no quartz was indicated. A total of 13 holes were drilled; 9 were on quartz bars. Although no exploitable deposits of gravel were found during this period of drilling, trace deposits of 15 to 30 cm of gravel were noted at the same elevation in nearly every hole, which indicated that this layer is widespread across the scene. Depths vary from 8 to 18 m. Gravel particles recovered from the holes were uniformly thin, flat quartz "poker-chip" disks, suggesting prolonged erosion in the swash zones of Pleistocene beaches formed by a receding ocean shoreline as delineated in the image scene. The four holes selected for negative verification showed only sand. Although this effort was not extensive enough to prove out for the entire scene, the results were encouraging and were used as part of the criteria for differentiating between the trace deposits of 30 cm or less and the thicker exploitable gravel deposits.

Following separation of the data for the Evangeline scene into ranges, each range was assigned a different color in the resulting image to permit correlation with field data.

The resulting revised scene for the south end of the Evangeline District indicates that most of the gravel bars are trace deposits and that isolated thicker deposits are present in several areas, possibly representing accumulations from estuaries cutting through the ancient delta. Unfortunately the indicated thicker deposits are not in accessible areas. However, the procedure developed will be used to identify potential drilling sites as other scenes are processed.

CONCLUSIONS

The data obtained indicate that Bands 1, 3, and 6 of the TIMS data displayed simultaneously can be correlated with subsurface gravel deposits in vegetated areas where some ground surface is exposed. How reliable the method is for locating exploitable gravel deposits will require more time and effort to determine. Future study will concentrate on drilling indicated deposits located adjacent to proposed construction projects.

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