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A Technology to Renovate the Search for New Mineral Deposits*

These methods have been refined and expanded to include exploration for lead, zinc, silver, tungsten, molybdenum, uranium, oil, gas, geothermal power sites and water resource evaluation.

(EDITOR'S NOTE: *This paper contains many illustrations which were originally presented in color. As the cost of reproduction of color for publication is virtually prohibitive, illustrations are herein shown in black and white. Some of the information content is thereby lost. Interested parties should contact the author for arrangements to see the original slide data.)*

ABSTRACT: *The era of shortage in America is now upon us with the current "fuel crisis" as its most evident effect. The country may be headed for severe shortages of other vitally needed minerals as well. It is with Divine timeliness that remote sensing has now arrived as a powerful new aid in the search for mineral deposits. Digital and analog methods of processing satellite data (Apollo and ERTS) have been combined into a systematic search strategy. Practical examples are shown where remote sensing is used with regional geomorphology, geochemistry and advanced mathematical modeling of ore distributions to zero-in on new deposits. Applications to discovery of aggregate limestone and porphyry copper deposits and new prospects are illustrated.*

INTRODUCTION

TWO MINERAL exploration programs conducted in 1971-72 were assisted by remote-sensing methods. The first was an application to search for a non-metallic commodity, aggregate-grade limestone in Florida. The second applied remote sensing to exploration for porphyry copper deposits in Arizona. The studies used remotely sensed data obtained by NASA and placed in the public domain at Sioux Falls, South Dakota and Albuquerque, New Mexico. Thus, the original data are available to anyone.

* Presented at the Annual Convention of the American Society of Photogrammetry in March 1974, St. Louis, Missouri.

The Florida example was spurred by the then current local shortage of building materials, including hard limestone aggregate. Suitable new quarry sites had to be found. The exploration area covered 3000 square miles and was characterized by low relief, dense ground cover and numerous lakes, ponds and swamps. The synoptic view provided by remote sensing of high-altitude aircraft and space photography was used to evaluate the likelihood of new limestone discovery.

Interpretation of data provided two answers, first that one-third of the area was covered with overburden so deep that it made commercial development of aggregate unlikely, and second, that in the remaining two-thirds of the area, nine sites of potential new aggregate deposits were discovered. Subsequent drilling of these sites showed that limestone existed at each and three had the commercial grade required for hard aggregate production. Leases were obtained and development is reportedly now underway. Discovery of all nine sites was accomplished in one-tenth the manpower time of previous effort per discovery.

In exploration for porphyry copper, the desire for new technology and improved efficiencies stems from limited future supplies, adverse balances of trade, and the increased difficulty of finding ever more subtly hidden deposits in the United States.

In the States of Arizona and New Mexico, which produce 55 percent of the United States supply of copper, there is very little vegetation, whereas the tone and textures that relate specifically to buried or partially exposed mineralization are subtle. They are amenable however to remote-sensing detection. Uniform definition of these tenuous copper ore guides is best made from the synoptic view afforded by space and can be objectively defined by color enhancement techniques. To this end an analog video image processor was used. The data were empirically treated to highlight known porphyry copper mines. The criteria were then applied to identification of new deposit sites. Again, aided by these techniques new copper bearing lands have been acquired, drilling has developed new resources, though at the time of this writing the full economic value of these sites has not as yet been completely assessed.

Discussion

Limestone

In 1972 west central Florida's rapid development created an expanding market for construction grade (hard) limestone, but local supplies were running out. Evidently, traditional methods of locating new deposits were too slow to meet the increasing demand. A new approach was needed and was available through NASA technology specifically in the form of high-altitude (RB-57) and satellite (Apollo IX) photography.

The area of remote sensor investigation using the photography shown in Figure 1 covered approximately 3000 square miles, characterized by low-relief, dense ground cover and many lakes, ponds and swamps. Apollo and RB-57 photographs of the region were analyzed to determine surface morphology (topography, drainage and probable rock type). Particular emphasis was given to identification of large-scale trends in the search area.

Figure 2 is an Apollo IX photograph with a basic resolution of approximately 350 feet. Regional structural trends are visible at *A* and *B* as north-northwesterly oriented interior

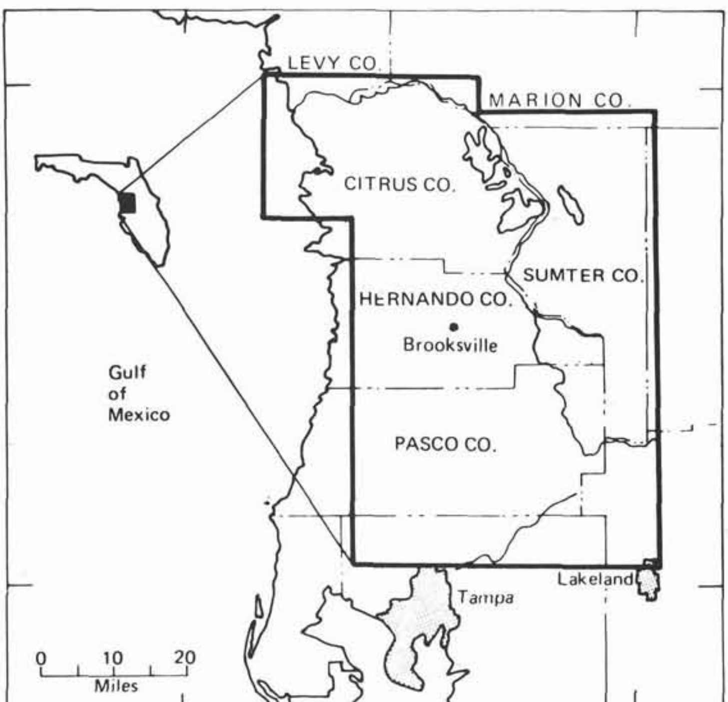

Fig. 1. Florida area of interest.

lowlands. The rectilinear trend of these areas indicates the regional structural grain.

Figure 3 shows the distribution of known quarries (×) in the northern part of the area. In the Crystal River, Brooksville, and Bushnell areas, they show the same northnorthwesterly alignment previously noted relating this inferred structural direction to the presence of known near-surface limestone deposits.

In low-relief areas, surface drainage patterns are useful for evaluating landform,

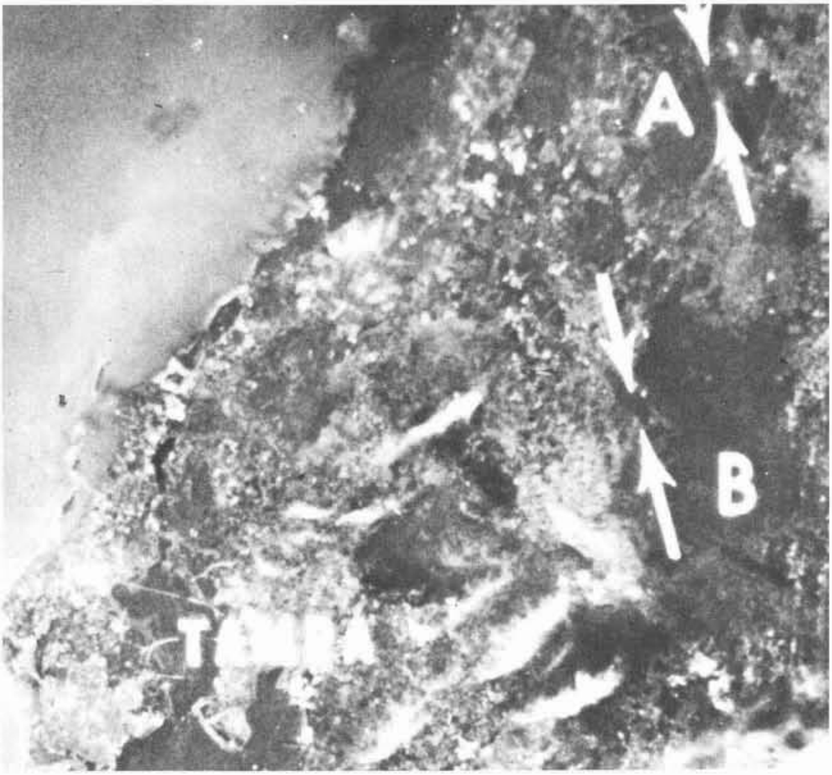

FIG. 2. Apollo IX photo of area.

FIG. 3. Land-use map.

structure, rock type and soil cover. Identification of these geologic features is primarily based on variations in distribution of stream drainage pattern, density, linearity and abrupt change in channel habit.

For example, in the southeastern part of the area at *E* in Figure 4, the Withlacoochee River abruptly changes direction from west-southwesterly to the north. Such a deviation suggests that the direction of flow in this part of the river was structurally controlled by subsurface uplift of erosion resistant material. That material could be older limestone strata presently close to today's erosional surface.

Not all of the area is equally favorable to the presence of limestone, however. At *F*, high drainage density characterization by numerous sluggish stream segments suggests a region of poor subsurface drainage. Such patterns indicate thick underlying strata of silts or clay, hence are unfavorable for a near-surface limestone occurrence. In addition to interpretation of drainage and topography, the high reflectivity of limestone was used to guide the choice of specific target sites.

Figure 5 was a color-infrared photograph of limestone pits taken from RB-57 photography at a scale of 1:125,000. Note that the pits at *C* may also be observed to the left of *A* on Figure 2. Smaller patches of ground having similar reflectivity may be seen in the pit area on Figure 5. It was interpreted that these represented areas of near surface *in situ* limestone and limestone rubble in tilled fields.

The potential of the survey area for limestone is summarized in Figure 6. It is a compilation of drainage and topographic morphology with surface reflectivity visually inferred from the remote sensing imagery. The nine numbered sites shown were thus selected whereas approximately one-third of the region (*I* and *II*) was ruled as unfavorable because of thick clay and silt cover. All favorable sample sites occur on two areas of structural uplift. The long axis *G-G'* trending north-northwesterly and a domal structure at *H*. Each of the nine promising areas were visited and surface sampled.

Samples of material cut from outcropping found at their respectively numbered sites are shown in Figure 7. Hard, highly fossiliferous limestone (Sample 1) was found near Brooksville and a similar limestone (Sample 4) was collected in the Crystal River area. Sample 2 was taken from the north bank of the Trans-Florida Barge Canal, whereas Sample 9 is a hard limestone with chert collected near the bend of the Withlacoochee River previously noted in Figure 4. In con-

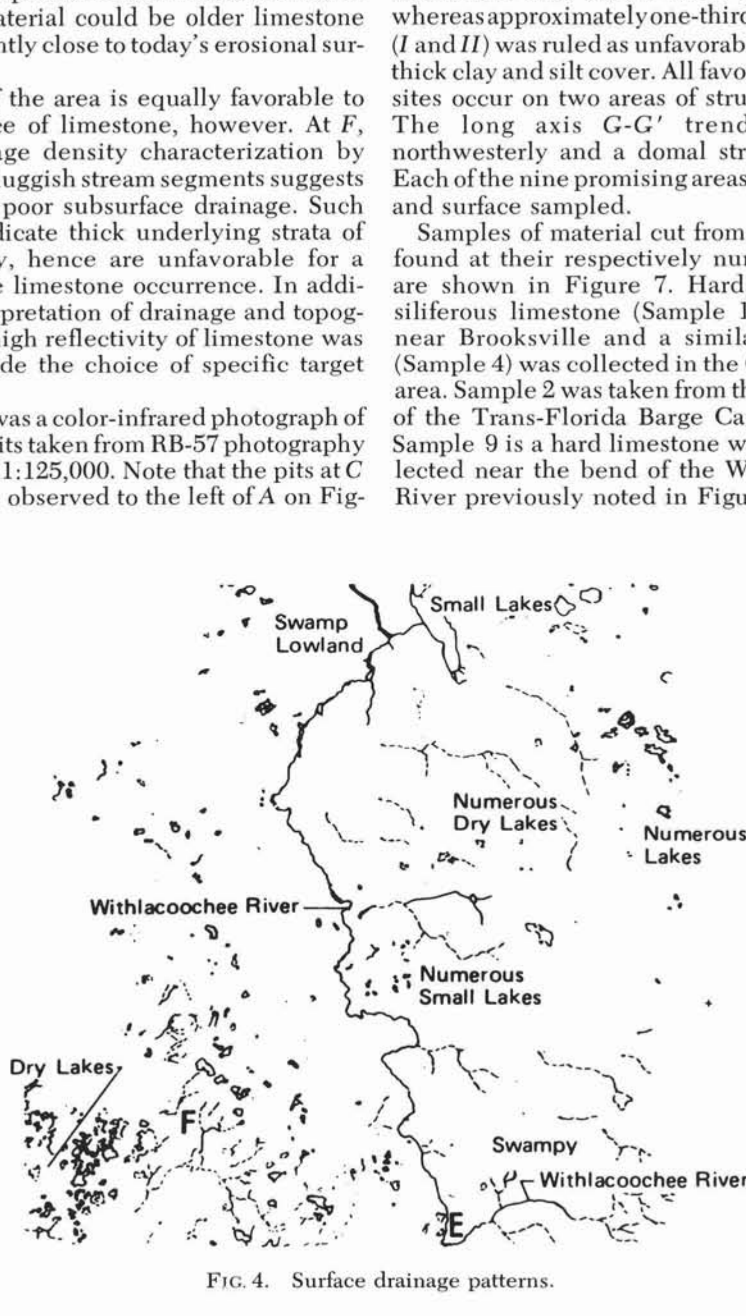

FIG. 4. Surface drainage patterns.

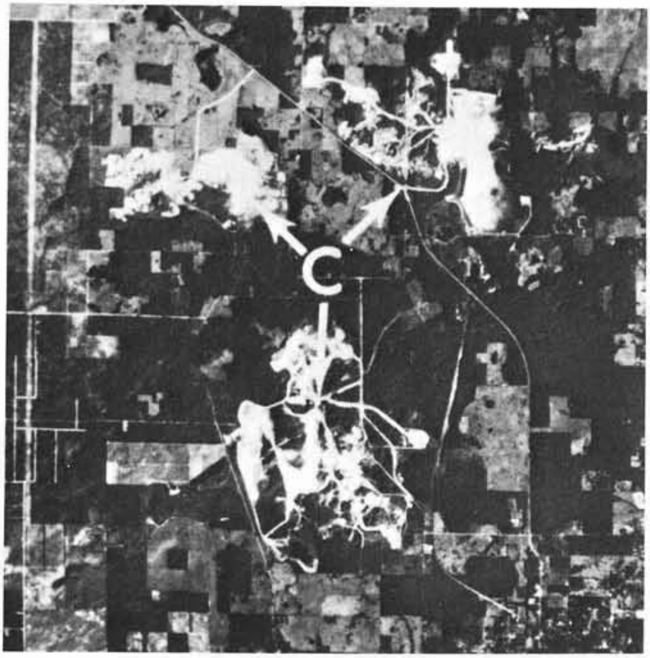

FIG. 5. Example of RB-57 imagery use.

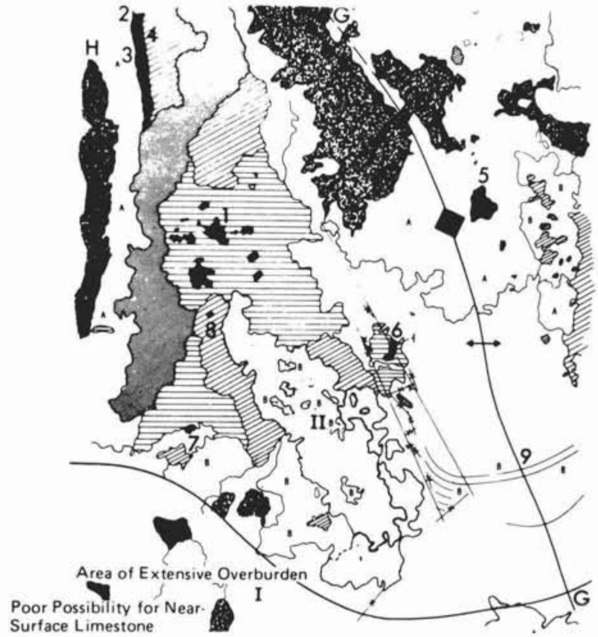

FIG. 6. Mineral resources evaluation map.

cluding this discussion of limestone exploration, Figure 8 shows the specific outcrop from which Sample 9 was taken.

In spite of its low surface profile and the locally dense surface cover, the combination of geomorphological and reflectivity interpretation from satellite and RB-57 photography allowed the samplers to go directly to this place. The total time required to evaluate 3000 square miles was less than one man month.

Based on these results, lands were ac-

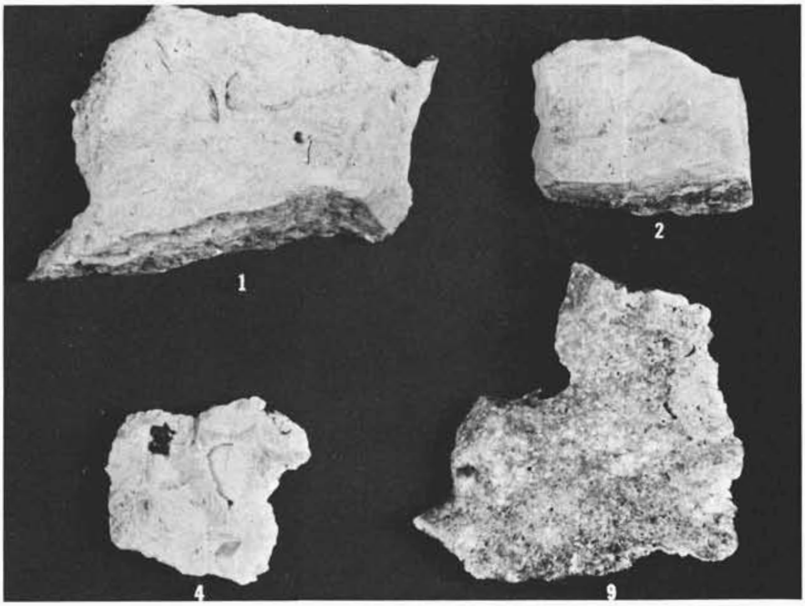

FIG. 7. Limestone samples.

FIG. 8. Withlacoochee River area.

quired, subsequent drilling has established three sites having adequate reserves to develop aggregate limestone pits, and two other sites have material suitable for manufacture of portland cement. Prospect drilling has also confirmed, as predicted, that no producible limestone seems to be in Area *I* and *II* of Figure 7.

COPPER

The problem of porphyry copper exploration in Arizona is quite different from that of the Florida limestones. Copper as well as many other metallic deposits tend to occur, or be found, in clusters. Although the location of many, if not all, of the major clusters of copper can be inferred from careful study of the geologic literature, additional specific deposits within a cluster area remain difficult to find. A typical cluster of copper-bearing mines and prospects may cover 100 square miles, whereas a single economic copper deposit may extend over only a square mile or less and is usually covered in part or totally by overlying, non-ore-bearing rocks. For these reasons the discovery and development rate of new economic copper deposits is but slowly increasing. Ideally, exploration for buried copper deposits would be greatly facilitated if they could be "seen" in spite of their cover. It is, in part, the objective of this paper to show that they *can* be seen using the blend of conventional geology, geochemistry, computer processing and remote-sensing technology to be described. It should be pointed out that from 30 to 70 undiscovered porphyry coppers remain to be found in the southwestern United States. Note that the median Arizona porphyry copper mine represents a $1 billion dollar gross business.

The advent of satellite and high-altitude remote-sensing data through a wide range of the energy spectrum, coupled with electronic processing (both analog and digital) of these data, offer mineral exploration a giant step forward. What we shall now discuss represents only a tip of the iceberg, for the full sweep of this technology is just coming into view.

A significant part of Arizona's copper production and reserves may be found within the region covered by Figure 9. The area bounded by the dashed line is that of a single Apollo VI photograph, covering approximately 10,000 square miles. All of the data have come from within this area. Color transparencies of the photoprint (Figure 10), as well as ERTS imagery and RB-57 photography were used for the remote-sensing evaluations.

In Figure 10 we can see the general loca-

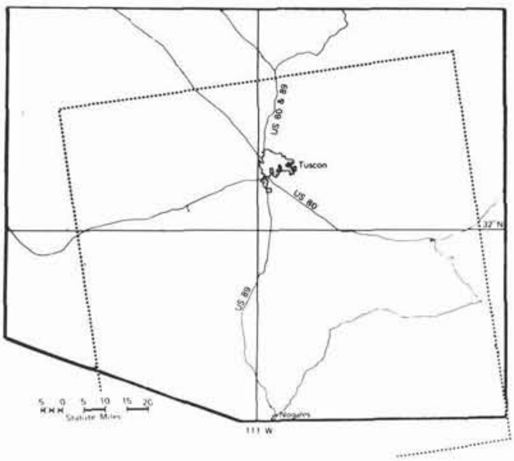

FIG. 9. Arizona area of interest.

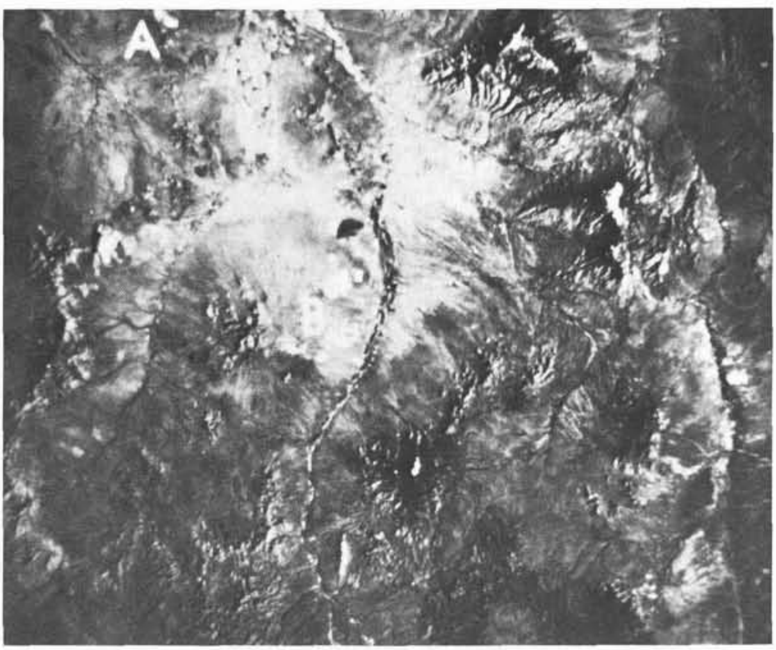

FIG. 10. Apollo VI photo of Tucson area.

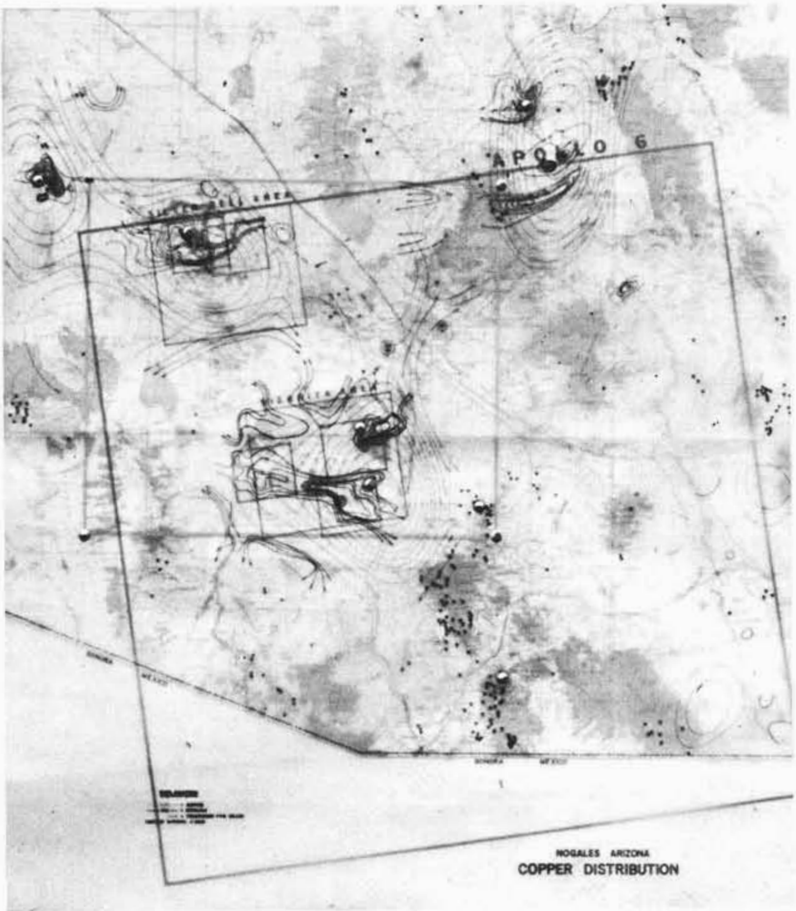

FIG. 11. Geochemical analysis of the area.

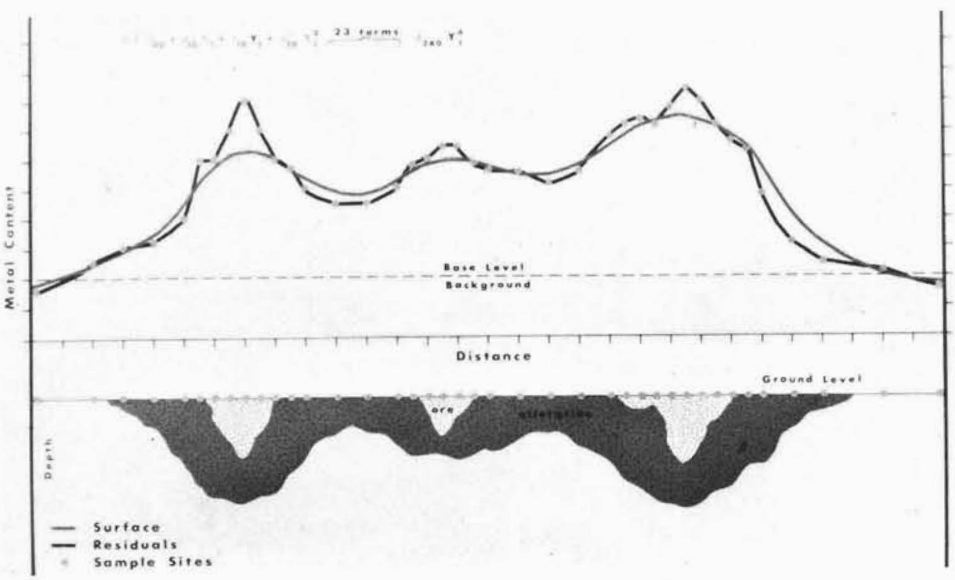

FIG. 12. Six-degree geochemical surface filling.

tion of six major copper deposits, two in the Silver Bell Area at A (also with a large tailings pile) and four in the Sierrita Mountain at area *B*. Actually what is seen most clearly are the man-made tailings piles and dumps surrounding the mines. In order to locate specifically the deposits (other than the pits themselves), and from these observations find new deposits, it is necessary to recognize those features that are present only in the subtle details of the film, or in the magnetic tape records. Moreover merely recognizing some of these data is not sufficient because there must be a basis for estimating their potential and real economic worth. It should be understood that over 6000 mapped mines and prospects exist in the southeast quarter of the State of Arizona alone. What then are these features and how do we contrive to see and economically evaluate them?

The best guides to the presence of a porphyry copper deposit are its geologic characteristics of rock mineralogy and more specifically the distribution of copper and related

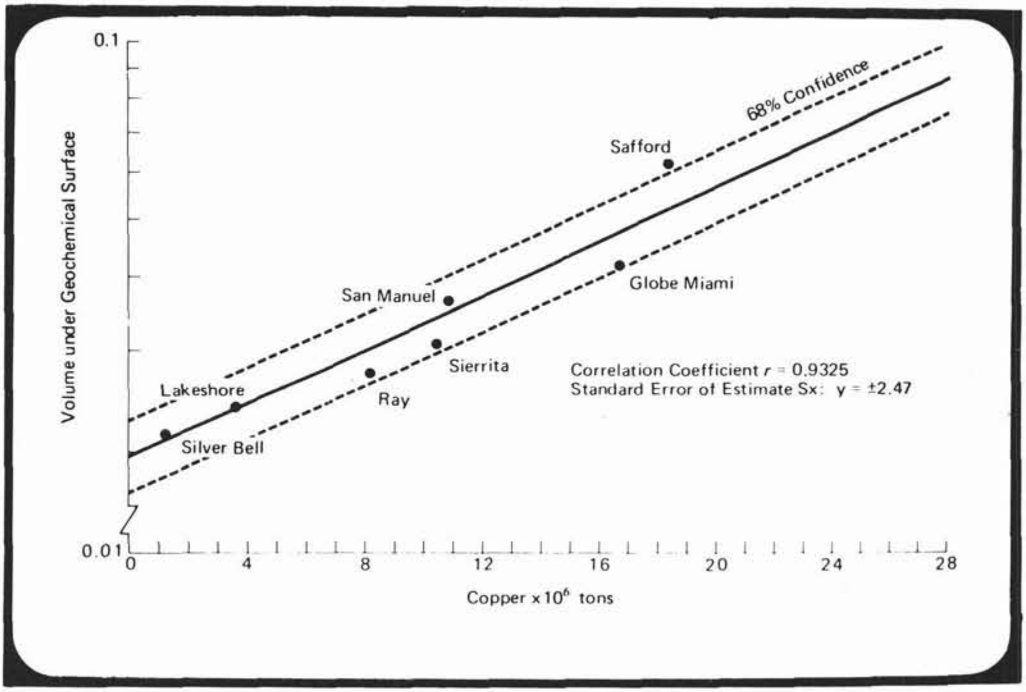

FIG. 13. Distribution of porphyry copper metal *vs.* geochemical response.

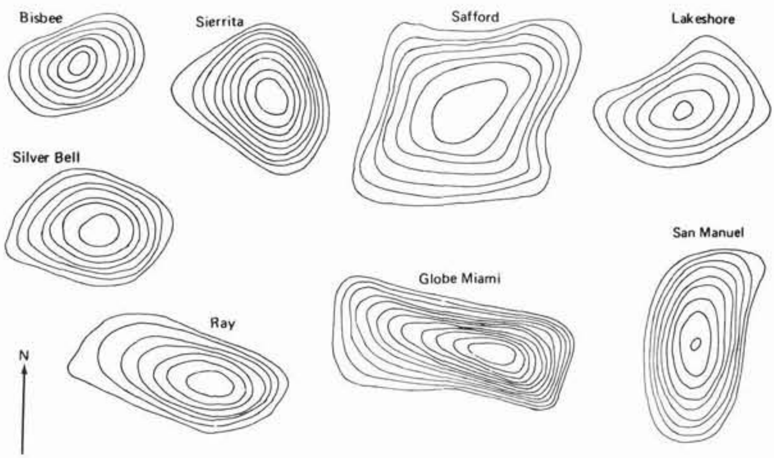

FIG. 13A. Geochemical anomalies of major porphyry copper areas in Arizona.

metals. It is the affect of copper, iron, potassium, etc., in terms of minute color changes, thermal conductivities and reflectivities that can be seen on the earth's surface. Specifically, we shall attempt to demonstrate a matching of mathematical models of the regional and local cluster concentration of copper to the remote-sensing data.

Figure 11 offers the results of a geochemical survey wherein deposit clusters and individual mine sites (red dots in the original) are contoured by a high-order *trend surface* equation. Four, and part of another, cluster areas are defined by the broad contour lines and numerous individual mine and prospect areas are represented by the smaller contoured areas superimposed on the regional pattern. Note especially that the Sierrita Mountains comprise one of these contoured clusters. A generalized cross-sectional relationship between ore and the various contour lines is shown in Figure 12.

The contouring of these clusters of ground surface copper concentration is achieved by statistically fitting approximately 500 stream-sediment samples to the area of approximately 10,000 square miles. These results supply two kinds of necessary information. Firstly, by integrating the volume area under the surface it is possible to *predict the probable number of tons* of copper metal to be found within a cluster area. Figures 13 and 13A show eight such contoured areas and their statistical fit to published production and reserves for each area.

Secondly, these models also determine (albeit crudely) the limits of areas of copper enrichment identifiable in the Apollo VI photograph (Figure 10) and from the later ERTS imagery of the same region.

An electronic image enhancement of the Sierrita Mountains is shown in Figure 14 where specific (Apollo VI) film-density levels relate to the areas of known copper enrichment. Mine dumps are seen as smooth medium gray tones related to darker gray deposit sites. These in turn are part of a broad region of mottled light gray that closely matches the regional contour lines of the corresponding mathematical model in Figure 11. Similarly the locally contoured areas on the regional trend contours fit the darkest gray areas that correspond to the known mines and possible new prospect areas. In other words we are literally seeing the distribution of copper at the ground-surface a-

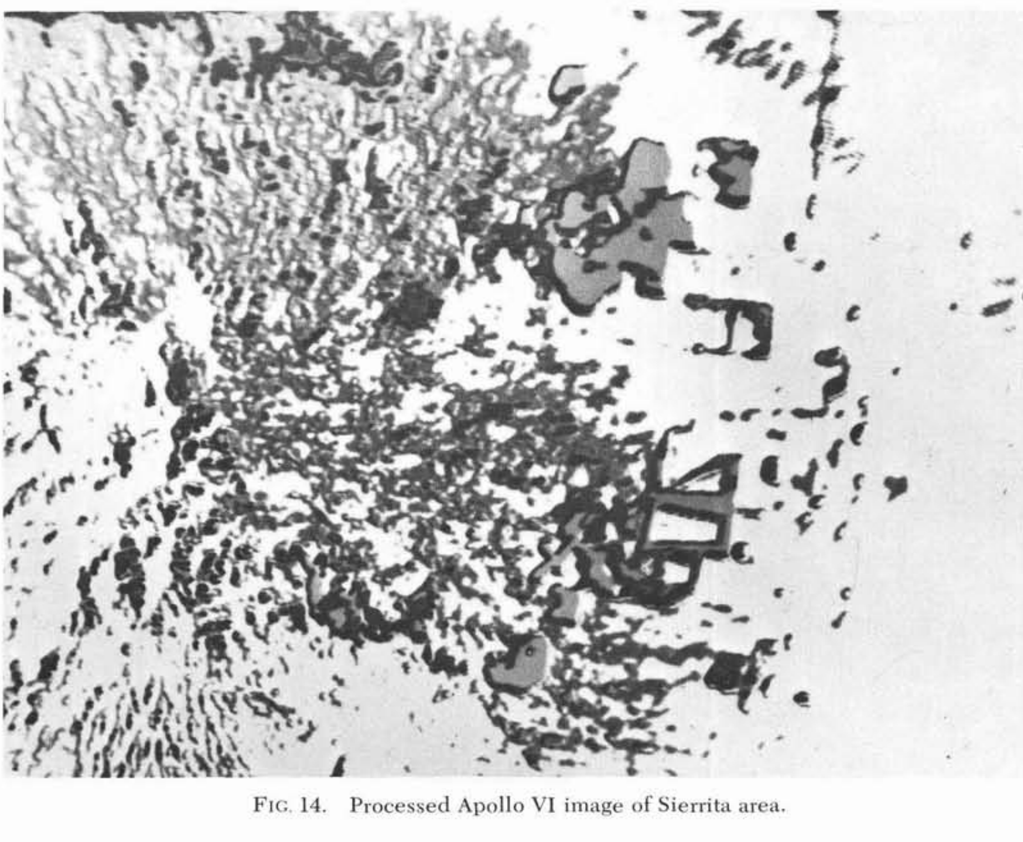

FIG. 14. Processed Apollo VI image of Sierrita area.

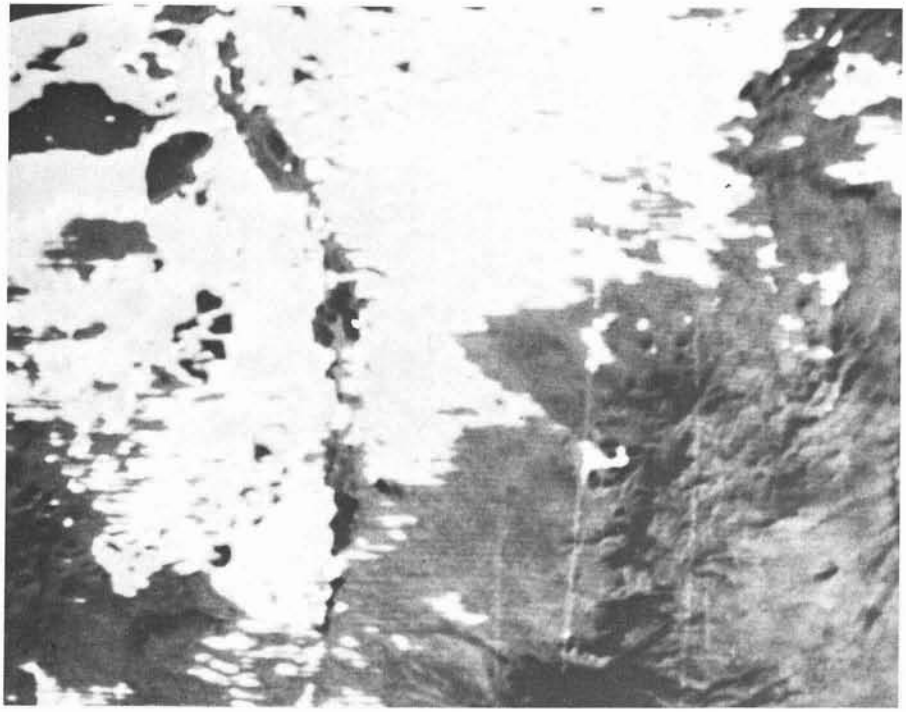

FIG. 15. Processed ERTS image of Sierrita area.

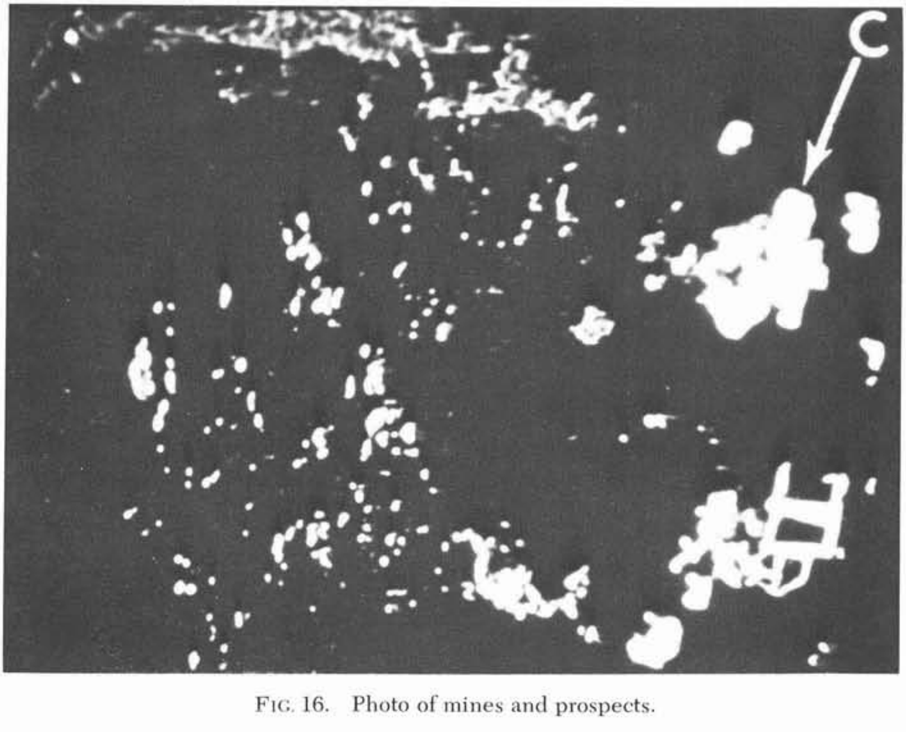

FIG. 16. Photo of mines and prospects.

cross approximately one hundred square miles.

A similar electronic processing is shown in Figure 15, this time of ERTS imagery and in arbitrary color assignment. Again a broad pattern in the yellow and orange tones (of the original) corresponds to the regional and local clustering of copper. The mine dumps are a dark brown while basalt is shown in black. Areas not affected by copper metalization have a green background. Within this broad pattern of increased copper concentration it is readily possible to focus attention on areas of maximum copper and copper related mineralization.

Figure 16 identifies only those areas within the approximately 100 square miles encompassing the Sierrita Mountain deposits. Mine dumps and tailings around the Pima-Mission pits at *C* are shown in yellow and orange, this

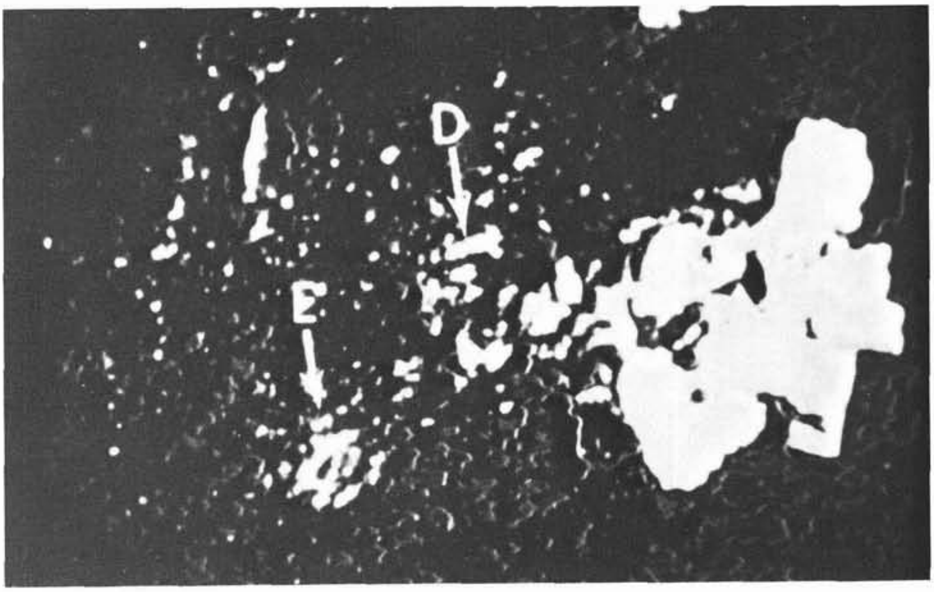

FIG. 17. Detail of Area *C* of Figure 16.

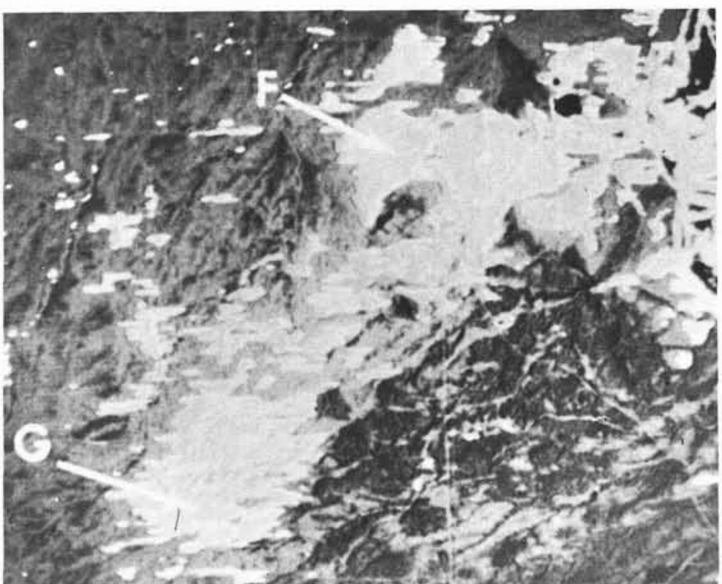

FIG. 18. Detail of Area *E-D* of Figure 17.

time against a blue background (all colors are arbitrarily assigned in the electronic image processing). The color of the Pima-Mission mine dumps now typifies other mine dumps and tailings to the north and south and also defines a discontinuous zone of small copper enriched alterations and mine dumps along a northwest trending major structure (the Saw Mill Canyon fault). In each of these instances metal enriched bedrock is exposed at the surface. It was noted, however, that areas of greenish hue appeared, particularly toward the top of the photograph. These are places geochemically enriched in copper but with varying thickness of soil cover, over the bedrock.

Converging on the 24 square miles immediately surrounding *C* some specific details of these contrasts can be seen in Figure 17. Again the results of man's activity are evident. At *E*, however, several million tons of low-grade copper has been drilled under shallow soil cover. The presence of this ore mineralization is clearly indicated even though the surface has not yet been disturbed by mining. The area at *E* remains an unevaluated prospect site, although mineral rights to the land have been acquired.

Figure 18 further reduces the area to six square miles using RB-57 photography. The letter *F* now becomes the area of drilled-out copper mineralization previously at *D*, and *G* now show the detail of the new prospect site at *E*. Subsequent detailed geologic study of the ground at *G* has changed the previously published interpretation for this area. It is now believed that significant new copper ore reserves may extend under lava and soil cover from the Mission Mine area at upper right of the photograph to the orange color anomaly at *G*.

Numerous other areas of the southwestern United States have been similarly evaluated. Two additional examples characterizing different geologic conditions of copper emplacement suffice to strengthen the assertion that remote sensing can help locate buried copper deposits. Both of these cases were evaluated by electronic processing RB-57 photography at other sites within the general survey regional originally defined.

In Figure 19 several tens of million of tons of copper ore have been drilled under a tree-covered hill at *T*. The orange tones in the original photograph again identify copper mineralization, this time in association with limestone. The hill with copper ore at its base is being eroded onto a gently dipping plain to the upper left corner of the photograph. The areas of blue-white color at *R* are places where fresh unaltered limestone is being mined for aggregate and smelter flux. Note particularly that the fresh limestone can be identified where it is being used for road metal *S* and as it washes down streams, again at *T*, even though it is being mixed with altered material of similar rock kind.

The deeper red tones shown in the original

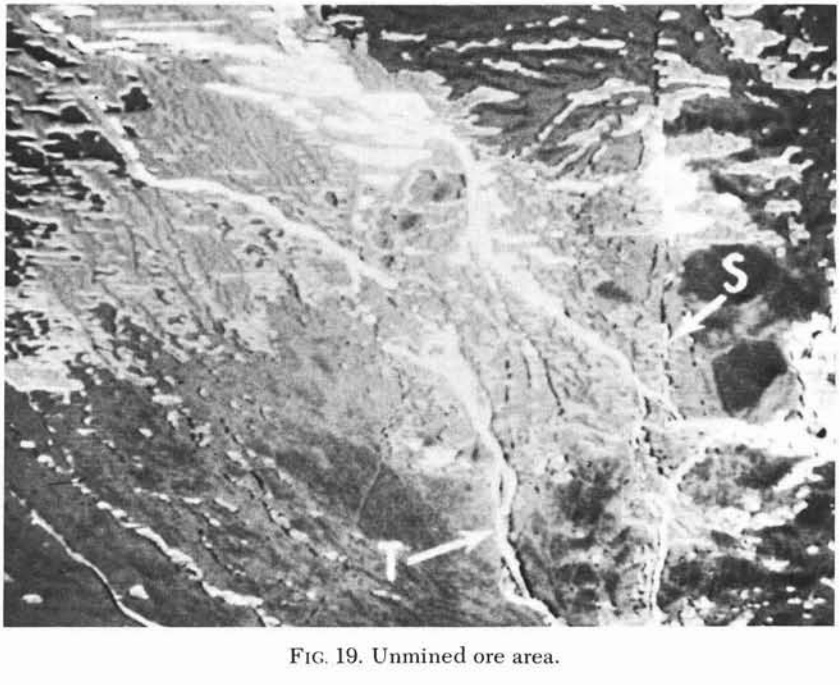

FIG. 19. Unmined ore area.

FIG. 20. Detail of covered unmined ore.

of Figure 20 are the result of matching a red filter to electronic processing of iron oxide staining. This staining is part of the alteration of older rocks overlying a drilled but as yet undisturbed porphyry copper deposit containing hundreds of millions of tons in ore reserves. In this example the relationship between the surface alteration shown in red is so close to the lateral distribution of the subsurface ore that drilling to sufficient depth anywhere in the red area would yield unquestioned evidence of the ore. The deposit dips steeply to the right and upper right of the photograph. At that edge it lies as much as 800 feet beneath the surface. The alteration observed here is virtually in place with little or no erosion.

CONCLUSION

Two examples of the commercial application of remote sensing to the discovery of non-metallic and metallic mineral deposits have been presented. Since this work was done, approximately two years ago, application of these methods have been refined and expanded to include exploration for lead, zinc, silver, tungsten, molybdenum, uranium, oil, gas, geothermal power sites and water resources evaluation. Let me therefore restate my belief that the search for new mineral resources stands at the threshold of a new dimension in achievement. The tools for this accomplishment will include those considered in this paper.