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Remote Sensing in Exploration for Mineral Deposits[1]

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Abstract

Remote sensing, a new term for an old practice of airborne exploration, has become a "cure-all" for the search for new mineral deposits. This paper seeks to evaluate those aspects of the technology which can be of use to the exploration geologist, and to place the various sensors in a priority listing for several types of geological targets. A point of significance to be clearly understood is that the "skin" (or penetration) depth of most sensors is shallow. Remote sensing really offers a chance to rapidly survey large areas, in seeking the diagnostic *surface* phenomena from more deeply hidden ore deposits.

Introduction

A review of the role of remote sensing in mineral exploration is timely, for there is a growing awareness of this new technology among persons concerned with developing natural resources. The literature of the photographic survey and engineering journals are filling with application papers, but thorough basic papers are still few in number.

Much of the remote sensing literature has evolved with the engineering attitude, or as it is often called, the "hardware" approach. Because of this, the technical papers are really summaries af applications of the "XYZ apparatus" to another field of research. The studies have invariably involved surplus military equipment, and hence their operating characteristics were dictated by demands other than geological. Typical of this is the lack of *calibration* in optical mechanical scanners because, as designed originally for the Services, no requirement existed for absolute (or in most cases the relative) temperatures of objects appearing on the thermal imagery. This of course is being changed, but truly calibrated thermal imagery is still not readily available.

A symptom of the engineering approach is the emphasis on a given wavelength band instead of on a problem. One hears of "the application of infrared to the study of . . .," of "the use of radar (or microwave) to . . .," rather than the "discovery of the ABC deposit of . . . by airborne techniques." We are still in the times of "let's try it and see" rather than those of the carefully thought-out experiment, using specifically designed and relevant apparatus.

This emphasis on an engineering approach is the logical result of a situation where state-of-the-art instruments have evolved faster than our ability to fully utilize them. Our greatest present need is for trained people to use existing hardware and to evolve new scientifically based techniques for their applications. It is especially important for these people to be aware of the multisensor approach, so that optimum sensor assemblages can be specified for a given task. Once the flight time of an aircraft has been funded, it costs little more to add one or two other instruments, and the data are often highly complementary.

The purpose of this paper is to define the data requirements for remote sensing of mineral resources, and accordingly the approach will be resource-oriented rather than instrument-oriented. "Remote sensing" as used in this paper will be restricted to the use of electromagnetic radiation from ultraviolet through microwave frequencies, although airborne sensing of the earth's magnetic field (a "force field" sensor) is obviously a significant and primary part of any multisensor approach. "Mineral resources" is used in the loose sense to include all surface and subsurface economic deposits, including ground water, sand and gravel,[2] and, because of the theme of the review,[1] Alaska will be emphasized.

In general, the geologically most useful sensors at present are those that form images—photography, side-looking airborne radar (SLAR), thermal infrared scanners and multiband scanners. The main advantages of these systems are their ability to cover large areas in a short time and to produce pictorial data (imagery) which can be interpreted after only a minimum of processing (data reduction). Non-imaging devices produce "line-trace" data, and are useful mainly for broadscale targets (e.g. water table, permafrost), or on an areally restricted basis where economic deposits are already suspected, as these deposits rarely extend over more than several square miles.

It would be nice if we had at our command a gold detector, an oil detector, etc., which we could mount

[1] Stanford RSL Technical Report 70-9—Presented at the Alaskan Remote Sensing Conference, Anchorage Alaska, Dec. 9, 1969.

[2] Typical mineral productions figures for the USA in 1965 show petroleum oil and gas ($14 billion), non-metallics ($5 billion) and metals ($2.5 billion). Sand and gravel are at $1 billion, or more than any single metal production.

TABLE 1

DEFINITION OF TARGET PHENOMENA AND REMOTE SENSOR SELECTION

Target	Target Surface Phenomenon	Remote Sensor Selection* — Photography: Black & White	Color	Color Infrared (CIR)	Multiband	Low Sun Angle (LSAP)	Multiband Scanner (Vis&IR)	Infrared Spectrometer	Side-Looking Airborne Radar (SLAR)	Infrared Scanner	Example (Fig. No.)
1. General Geology (a) Rock distribution	tone or color differences	B	A	C	D	.	E	.	.	.	1
	vegetation differences	.	.	A	B	.	C	.	.	.	
(b) Rock type	color	.	A	B	C	.	D	.	.	.	
	thermal property differences	.	.	.	.	.	.	.	.	A	
	surface texture	B	.	.	.	C	.	.	A	.	2,9
	chemistry, mineralogy	.	.	.	.	.	.	A	.	.	3
(c) Structure	surface relief, lineaments	.	.	.	.	A	.	.	B	C	4,5,6
2. Ore Deposits	color of alteration zone	.	A	B	C	.	D	.	.	.	7
	texture of alteration zone	.	.	.	.	B	.	.	A	.	
	vegetation differences	.	.	A	B	.	C	.	.	.	
	lineaments	.	.	.	.	A	.	.	B	C	8
	thermal anomalies	.	.	.	.	.	.	.	.	A	
	gravel and placer deposits	D	.	.	.	B	.	.	A	C	9,2
3. Hydrocarbons	source rock and reservoir rock distribution	as	1.	(a) and	1.	(b)	above				
	structural trap	D	.	.	.	A	.	.	B	C	
4. Ground Water	topography and drainage	.	.	.	.	A	.	.	B	C	
	vegetation differences	.	D	A	B	.	C	.	.	.	11
	soil moisture	B	.	.	.	.	.	.	.	A	6
	springs	.	.	.	.	.	.	.	.	A	
	permafrost indicators	see	6.	below							
5. Geothermal Energy	convective and advective heat transfer	.	.	.	.	.	.	.	.	A	12
	vegetation anomalies	.	.	A	B	.	C	.	.	.	
	discoloration	.	A	B	C	.	D	.	.	.	
6. Permafrost	polygonal ground	A	B	.	.	D	.	.	E	C	
	patterned rocks	A	B	.	.	C	.	.	D	.	
	thermokarst structures	A	B	.	.	C	.	.	D	E	
	beaded (button) drainage	A	D	B	.	.	.	.	.	C	
	pingos (hydrolaccoliths)	A	B	.	.	C	.	.	D	E	
	vegetation differences	.	.	A	B	.	C	.	.	.	

* Letters indicate approximate order of probable use. With varying conditions these priorities will of course change. Availability and cost are considered, so that first priority sensor may not be the best, but simply easier to obtain and use.

Note: Figure 10 should be inserted in last column of Target 3.

in a suitable aircraft and fly over unexplored terrain until a buzzer indicated a deposit. Unfortunately, these devices do not exist. Most economic mineral deposits do not occur at the surface, but are buried at various depths, and *the majority of remote sensors do not penetrate far beneath the immediate surface skin.* As petroleum industry people well know, the presence of oil is confirmed *only* when oil is actually brought to the surface in a drill-stem test. But the whole basis of oil exploration is to choose a drilling site on the basis of favorable *indirect* indicators—a sedimentary basin with hydrocarbon source rocks, suitable reservoir rocks and favorable entrapping conditions. So it is with remote sensing. Remote sensing methods offer the potential for rapid coverage of large areas in seeking *surface phenomena* that may indicate the presence of a given mineral resource.

Many authors have described the mineral resource of regions (such as Alaska), that is, the "targets" for remote sensing. We must define the surface manifestations of such targets and then select the optimum sensor(s) to detect these surface expressions. Let us place emphasis upon defining those surface phenomena that are amenable to detection by state-of-the-art remote sensors. It will be an incomplete listing and certainly any reader could add to it. While we show "General Geology" as a target, for ease of discussion, most certainly, broad geologic features would be part of any mineral exploration study. (Table I is a summary of the following discussion.)

Discussion of Possible Targets

General Geology

Surface rock outcrops may be differentiated, identified and mapped in several ways. A difference in tone or color of the rocks may be readily recognizable on air photos, especially color film (Fig. 1). Where subtle color differences are present, multiband photography or multiband scanners may be required. For successful use of multiband surveys, it is neces-

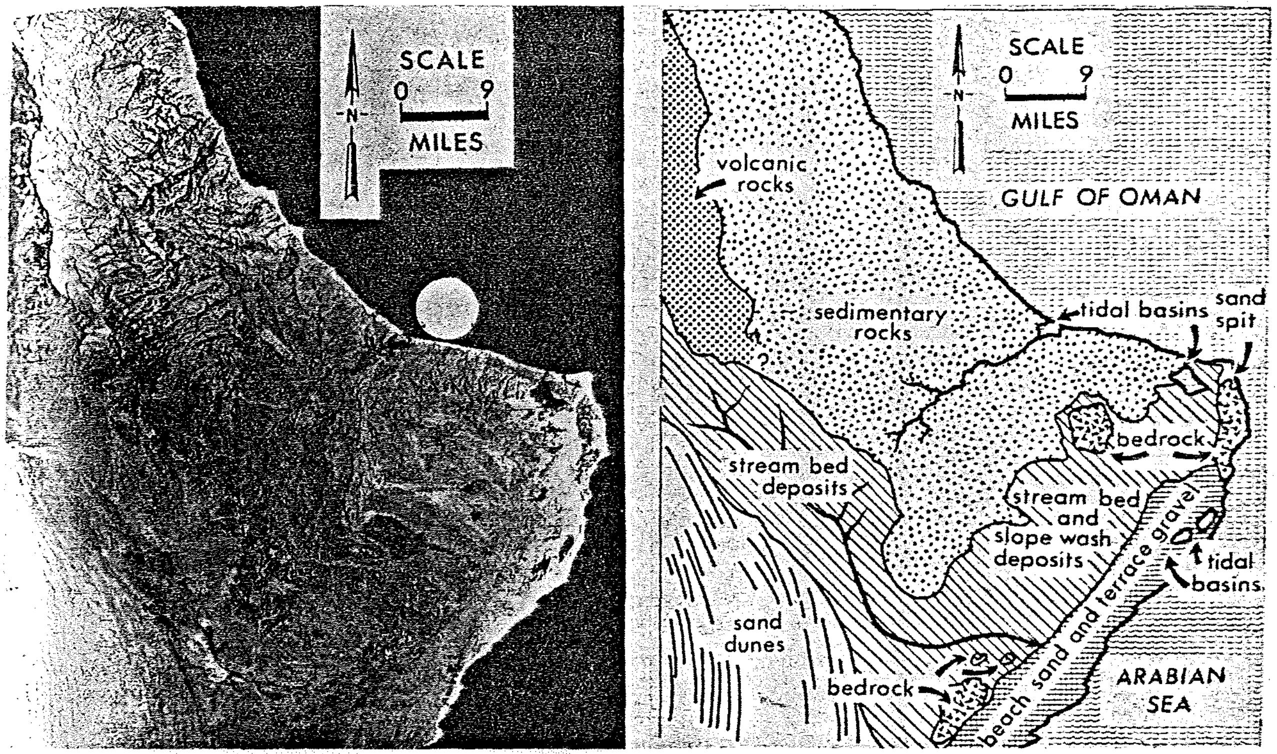

FIG. 1. Example of the simple geological map that can be derived from a (good) space photograph. Black and white copy of Gemini IV photograph (S-65-34661) over Saudi Arabia, with a simple geological map prepared from the same photograph. The area shown includes volcanic and sedimentary rocks, stream deposits, and sand dunes. Photograph by NASA, map by the U. S. Geological Survey. (By kind permission of GEOTIMES, 4/1/66.)

sary first to determine the reflectance spectra of the terrain features involved, in order to specify the passbands of the filters so that the data will yield the maximum contrast, or seperation. Unfortunately, although this is clearly a prerequisite, it has been seldom done, and usually instruments are flown on the "look and see" basis.

Surface textural differences are also mappable on conventional photography, side-looking airborne radar (Fig. 2), and high-resolution low-sun-angle photography (LSAP, see later discussion).

Differences in thermal properties serve to differentiate surface materials by producing different temperatures. Solar heating rates will vary during the day and season, and similarly, cooling rates at night will be different. The resulting patterns of temperature distributions can be mapped with optical-mechanical scanners, preferably operating in the 8–14 μm wavelength region, for example. A prior knowledge of the approximate thermal parameters (especially thermal diffusivity[3]) of the surface materials involved is most desirable, since the thermal survey can then be flown when temperature differences between the materials are maximized, with the resulting infrared imagery showing greatest true contrast between surface materials. Such knowledge is mandatory for the fullest return from the interpretational phase.

Rock distribution often can be determined by mapping vegetation. At present, remote sensing methods have been applied more successfully in agricultural studies than in geology (perhaps because there are marked differences between plant species whereas rocks show a continuum). This success can be carried over by a re-emphasis of geobotany, that is a usage of the often-noted (but rarely used) close association between soils and rock and the plant life growing on them. A vegetation cover is generally regarded as a nuisance in geologic remote sensing, but it can often provide valuable information on the characteristics of rock and soil beneath. Plants grow selectively on different types of terrain, but generally we do not use this simple fact to our advantage. Optimum sensors for vegetation discrimination are color infrared film (CIR), black and white infrared film, multiband photography and multiband scanners. As in the case of direct rock discrimination, it is necessary to obtain reflectance spectra of plant species in the area of interest before selecting film/filter combinations of specifying information channels for the multiband scanner.

Rocks may be identified by their mineral content.

[3] Thermal diffusivity $(\alpha) = \dfrac{\text{Thermal Conductivity (K)}}{\text{Density}(\rho) \times \text{Specific Heat }(C\rho)}$.

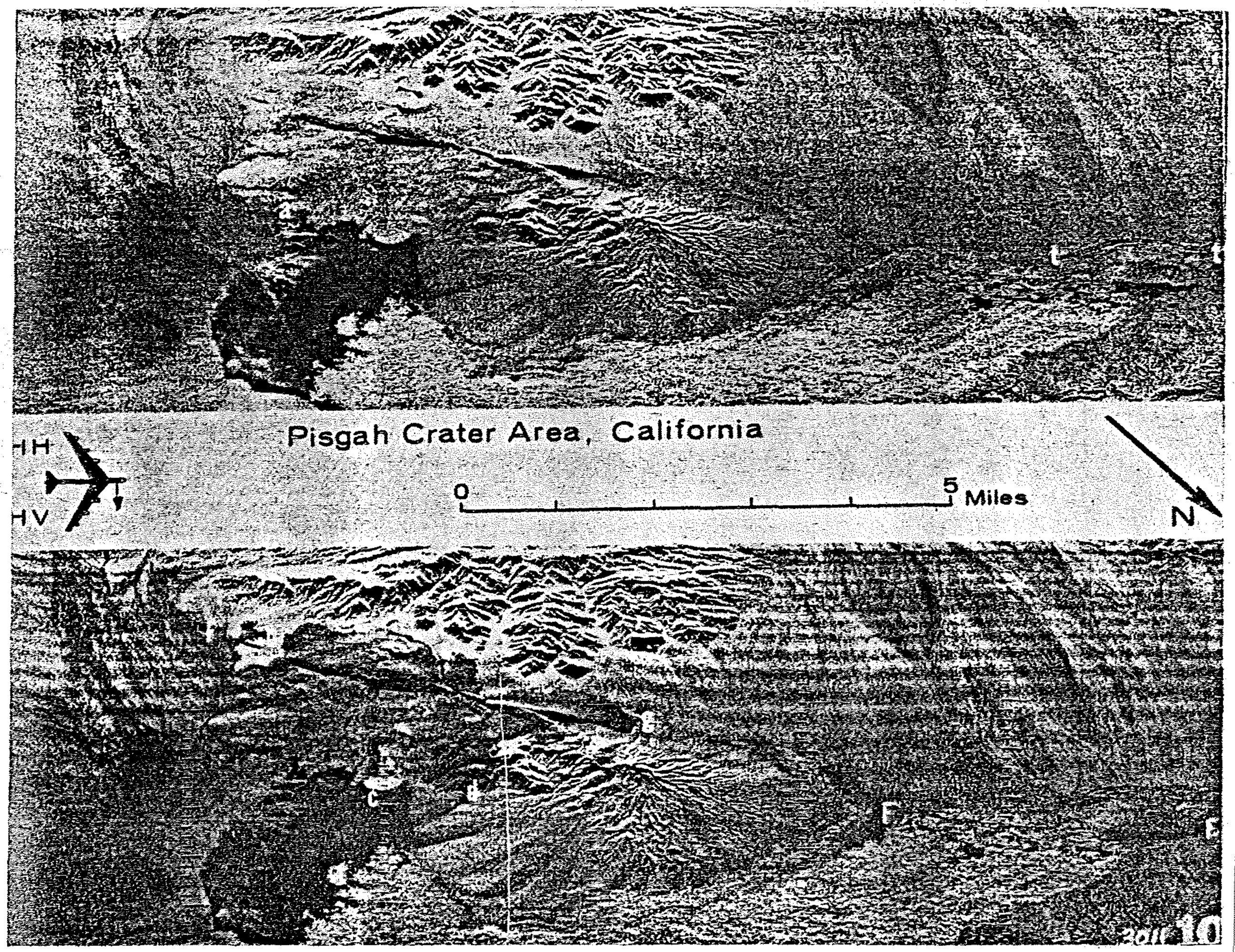

FIG. 2. K-band Radar of Pisgah Cratar area, Barstow, California (Dellwig and Moore, 1966). Simultaneously produced plane-polarized (upper) and cross-polarized (lower) radar images of the desert terrain just south and west of Pisgah Crater, the lava flows from which run from lower left to lower right. A collapsed lava tube may be seen at (t-t). In this terrain there is a considerable difference between the two images, and the older Sunshine lava flows can be readily differentiated from the surrounding alluvials of several ages (at a,b,c,d,e, and g). The Sunshine Fault (FFF) is penecontemporaneous with some of the flows, but also is younger than the alluvial fan it cuts and displaces vertically near the center of the image. The playa lake below (c) produces a dark area on imagery because the fine-grained sediments form a smooth surface which acts as a specular reflector to K-band radiation. Illustration from negatives provided by CRES, U. of Kansas, and further annotated by present authors.

Variations in the Si-O-cation crystal lattice of a silicate mineral produce characteristic emission spectral signatures around 9 to 11 μm. These spectra thus serve to identify minerals and mineral assemblages. An airborne infrared emission spectrometer has been flown to record these spectra (Fig. 3), but this is still a complex experimental process compared to the others we suggest (Lyon and Patterson, 1966, 1969).

Geologic structures frequently exert a strong influence on surface topography as the differences in resistance to erosion of rock units tends to produce relief which is conformable to rock distributions. Structural discontinuities, such as fractures, joints and faults, most often are more easily eroded than surrounding rock, and thus produce linear depressions at the surface. Where topographic relief is great, conventional aerial photography may be suitable for mapping structures, but there is little doubt that low relief can be enhanced by low-sun-angle photography (LSAP), (Lyon and others, 1970). Very subtle topographic changes can be readily seen on LSAP (Fig. 4) because sun-facing slopes are illuminated and back slopes are in darkness. Optimum conditions obtain when the light is at grazing incidence to most back slopes and at a high angle to the trend of ridges.

Analogous to this type of photography at low illumination angles is side-looking airborne radar (SLAR). While the geometric considerations vary,

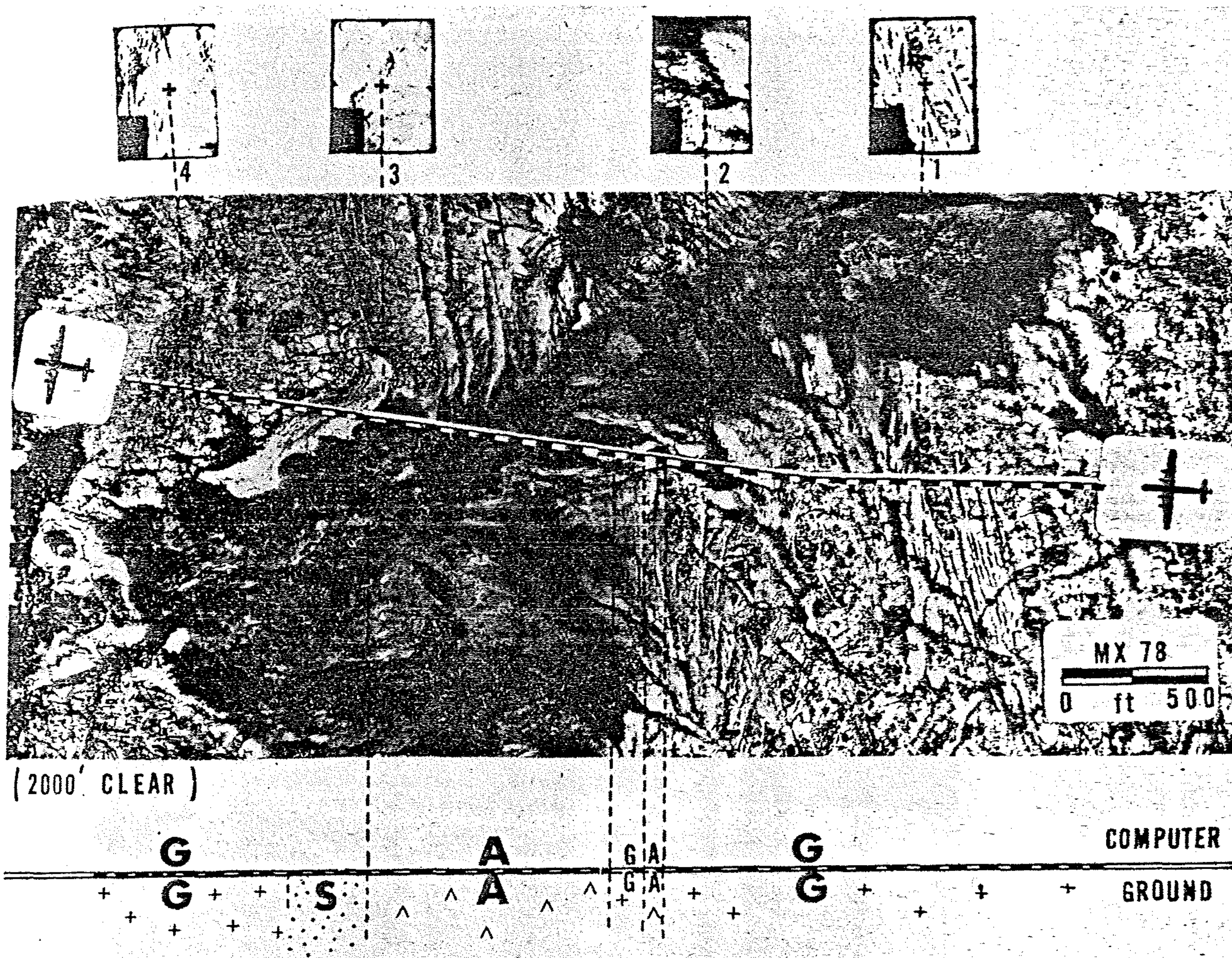

FIG. 3. Results from measurement of spectral infrared emittance of terrain, Sonora Pass, California. This figure consists of a series of RC-8, B/W photographs, used as a mosaic, to show the ground trace of an airborne (8 to 13 μm) IR spectrometer experiment (Lyon, 1965, Lyon and Patterson, 1966, 1969). At 2000 feet above terrain this is 15 feet wide $\times$ 40 feet long, spectra being taken at a rate of six per second. The lower bar shows the geology (called "ground") as quartz monzonites ("granite"), gray, with andesitic volcanics (darker). Some rhyolite mixed with basalt debris occurs in patches, and some meadows are shown. Area is Sonora Pass, central California, in the Sierra Nevadas, at about 10,000 feet elevation. Upper part of the bar shows the decisions made by the computer program which analyses the spectra, using a discriminant analysis (BMDO7M).

the expected result is similar, in that slopes facing the aircraft give strong returns (bright on imagery) and the far slopes produce a jet-black radar shadow (Fig. 5). Maximum contrast is obtained when the aircraft is flying parallel to the trend of geologic structures, with the radar beam perpendicular to ridges.

Structural discontinuities can be detected or enhanced on thermal infrared imagery when flown under suitable conditions. Figure 6 is an example of such imagery from Southern California, where soil moisture changes along a fault (f) create a cold surface anomaly. Another fault (at e) images cold either because of similar moisture conditions or because of cold air ponding against the topographic low associated with the fault (Sabins, 1967, Kilinc and Lyon, 1970).

Ore Deposits

A common surface indicator of the emplacement of ore minerals is an alteration zone in the host rock. Color changes accompanying this alteration are detectable on various films and by multiband scanners. A particularly common alteration product in basic rocks is oxidized iron, characterized by a rust-red color. Conventional air photography generally will not detect this because panchromatic film has a low sensitivity to red, yielding a dark tone against the dark background from the basic rocks. Color photography will help locate such an alteration zone, but

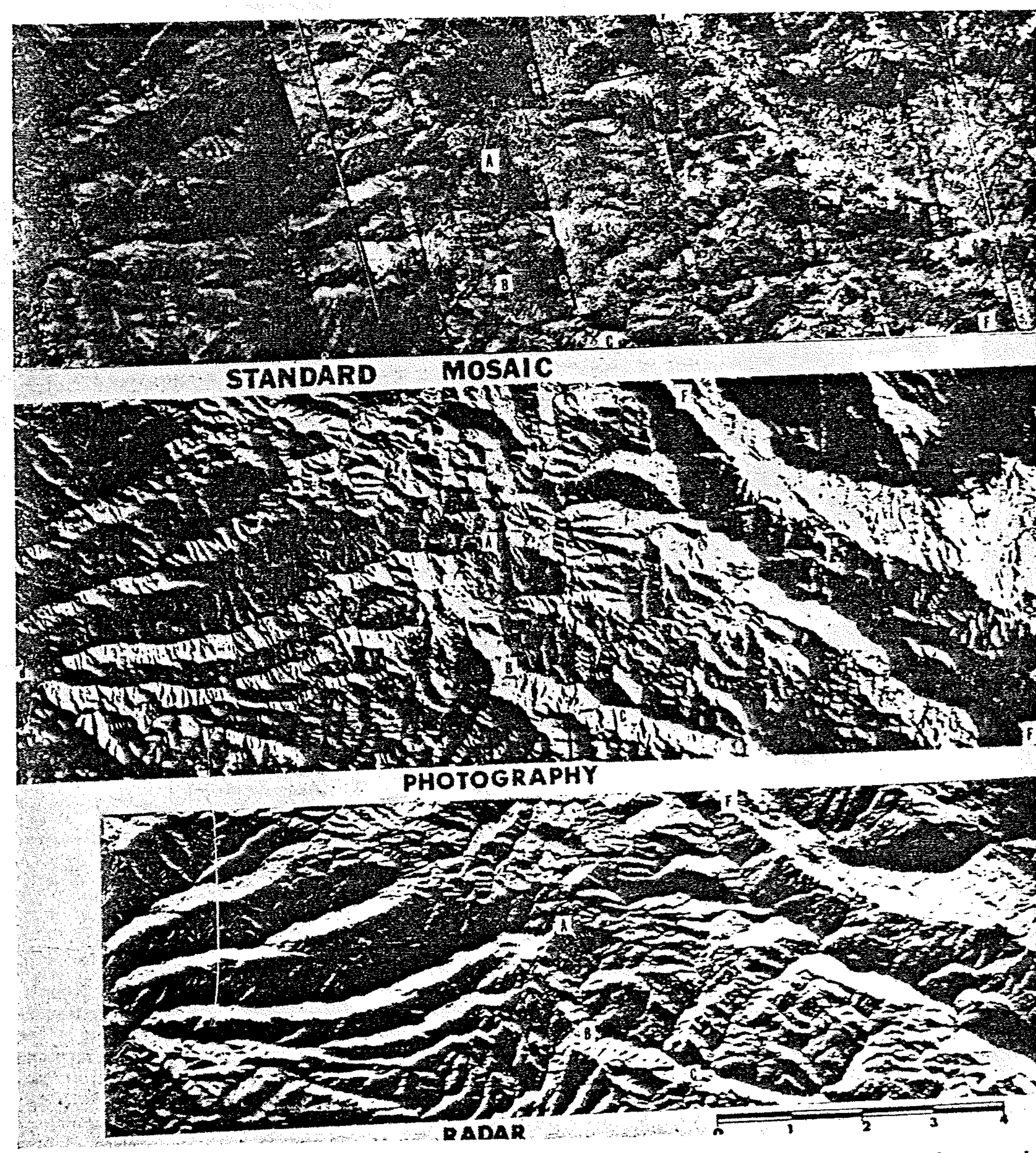

FIG. 4. Comparison between mosaics of conventional high sun-angle photographs, low sun-angle photographs and side-looking radar. In this figure three data presentations from the same Central California Coast Range area are shown, a *standard mosaic* (top) of regularly available (high sun) photography prepared by the U. S. Geological Survey. South is towards the top, and the 121°37′30″ longitude line traverses the right hand edge of the print. The area is 13 miles southeast of Livermore, California, in Franciscan metavolcanic and volcanic (greenstone) rocks, intruded by some serpentine. Bald Mountain occupies the center of the area near (A). Scale is in miles. The lowest print is an enlargement of K-band side-looking *radar* of the same area shadowed from the top (south). The central print is "pseudo-radar" *photography* (Lyon *et al.*, 1970) prepared to simulate radar, using conventional vertical aerial photography but with *low* sun-angle, calculated from an "average" radar illumination angle (27°). The key points in this analysis are that both lower prints show the major fault -FF- ("aerial photo lineament" on San Jose sheet, 1:250,000 scale, California State Geologic map). Mitchell Ravine (BC) is equally well shown on each, but its sharp southward extension (BA) is most readily visible or is readily visible only on the "pseudo-radar," and missing entirely on the K-band radar. Equally well, a whole family of other N-S linears appear on the photography at low sun, but are absent from the radar. This is probably because they are so closely parallel to the radar beam. The low sun photography was taken at 27° sun (1630 hours, Mar. 17, 1969) using a K-17B camera, 6 inch lens, 60% overlap, and minus blue filter. Film was Plus X Aerographic, taken at 20,000 feet. Original mosaic was at 1:40,000 scale and rephotographed to increase contrast.

especially useful is CIR film, because the red color will image yellow against a dark, nondescript background (Fig. 7). Needless to say, these methods require bright, high-angle sunlight.

Because ore solutions tend to follow zones of weakness in the host rock, other surface indicators of ore may be faults and other lineaments, and zones of microbreccia, or crushed rock. Such zones gen-

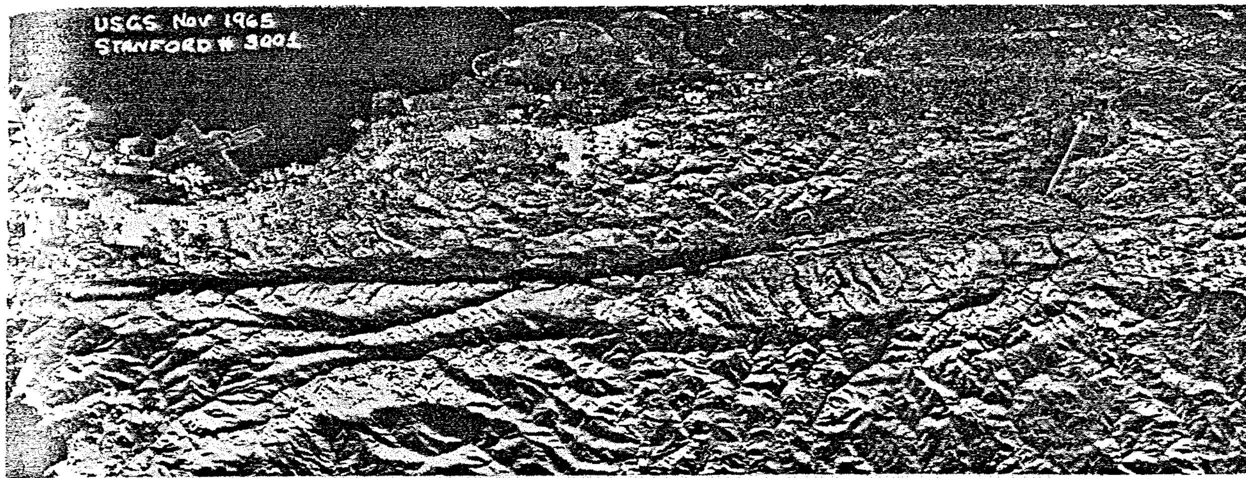

FIG. 5. Side-looking, K-band radar of San Francisco Peninsula. A direct extrapolation from vertical aerial photography to side-looking radar is an easy step, as they have many aspects in common. The low illumination angle (18 to 70 degrees) provides a strongly shadowed, three-dimensional view, which is increased by the small scale of presentation (1:200,000). This is a slant-range view, which explains much of the distortion. In this view the San Andreas Fault runs horizontally through the print, with the water-filled depressions along the fault trace showing as black linear patches. The higher proportion of metal and the squaresided buildings in the residential areas along the peninsula are shown by the brightest spots of high radar reflectance. Little differentiation of rock type can be made, except by topography which is slightly different for various materials. Rows of trees lining the roads near the lakes are clearly seen (Eucalyptus, mainly), and the grassy areas on either side of the Stanford Linear Accelerator (center right, long white strip), appear as darker patches with occasional trees as brighter grey spots. Following detailed field checking done in the areas near Stanford, each bright spot can be correlated with a tree, rock outcrop, or metal object. The image is best used at about a 3× enlargement, at a scale of about 1:62,500. There is no evidence seen here to support the statement that K-band radar "penetrates" trees and grasses, as each may be detailed on the image and correlated in the field. The image is plane-polarized, but the cross-polarized equivalent, produced simultaneously, did not reveal additional geological features (see, however Fig. 2). The reflections from the residential areas "drop out" on the cross-polarized image, and some agricultural crops in fields can be determined by this effect. Illustration from negatives provided by CRES, U of Kansas.

erally express themselves as linear topographic features, which are detectable by LSAP, SLAR or infrared scanning (Figs. 4, 5, 6 & 8). Where there are massive concentrations of metallic ores at the surface, the return energy of SLAR is theoretically increased, although this has not been demonstrated, perhaps because of the small size of such features relative to the 1:200,000 scale of most SLAR.

Vegetation differences, as discussed above, can be particularly important around ore deposits. As an example, it has been shown that uranium-vanadium deposits of the Colorado Plateau markedly affect surface vegetation (Cannon, 1952). Plants growing in areas of oxidized ores show chlorotic symptoms and dwarfing whereas those rooted in unoxidized ore are little effected. Uranium-tolerant species have been recognized whose mapped distribution accords with that of carnotite ores. CIR, multiband cameras and scanners have the ability to discriminate species *when* their reflectance spectra are known.

Much has been mentioned in the scientific literature concerning the exothermal chemical reactions accompanying oxidation of sulfide ores or the build-up of radiogenic heat from uranium and thorium deposits. It has been assumed that such heat sources should be detectable with an airborne infrared scanner, but this capability has not been demonstrated. Under most natural conditions, the possible surface temperature anomaly above such a heat source would be about equal to the noise-equivalent temperature difference, i.e., the sensitivity, of state-of-the-art scanners, but generally far below that due to the daily input of energy from the sun (at least at moderate latitudes). This does not rule out the possibility of detection, however, if scanner data are collected either by a dual channel or multichannel infrared scanner or from repetitive flights and the data then treated statistically to seperate noise, which is random, from real information. Any program to use an infrared scanner to explore for heat conductive phenomena must be prepared to collect multiple data and employ statistical reduction methods.

Gravel and placer deposits require remote sensing techniques which discriminate the surface roughness effects or the thermal properties of the gravel bodies. The energy levels in radar returns is directly affected by surface roughness and thus one can distinguish gravels from fine-grained alluvial surfaces (Fig. 9, 2). Thermal properties also serve to seperate gravels from fine-grained deposits, particularly where there are resulting internal drainage differences. Especially in areas of permafrost, these thermal effects are detectable on infrared scan imagery.

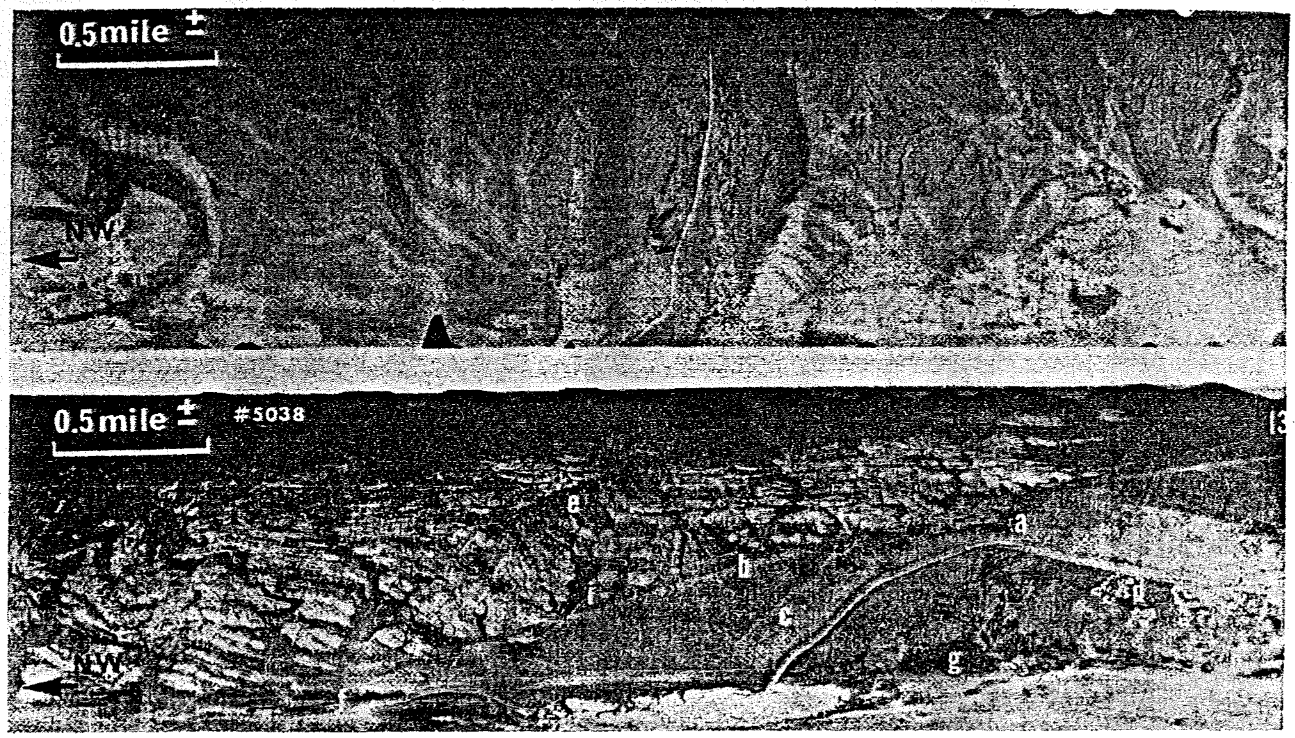

FIG. 6. Infrared imagery at a low altitude over the Indio Hills, California. Two strips of infrared scanner imagery flown at midnight in 1963 over the Southern California desert hills just east of Indio, near Palm Springs, California. Scanner was a Reconofax IV filtered for the 8 to 13 μm bandpass. (Imagery after Sabins, 1967, with further interpretation by the present authors.)

a = 2 small Salt Cedar trees (white = hot) in cool (dark) alluvium.
b = bull-dozed strip covering buried gas transmission pipe line (soil is now changed in texture).
c = bull-dozed strip with all top-soil removed to make the large dyke (just below c,a, and above d).
d = desert shrubs with dead center (sand filled), and activity growing edges (white-hot-alive).
e = fault and drag fold in vertically bedded thin bedded shales (darker) and sandstones (lighter).
f = cooler linear features along fault (f–g) (probably raised-water table effects).
g = same as f.
h = some brush-clearing activity almost parallel with the fault (f–g).
i = black top (asphalt) road across desert hills for a nearby power transmission line (towers not resolvable at this scale.

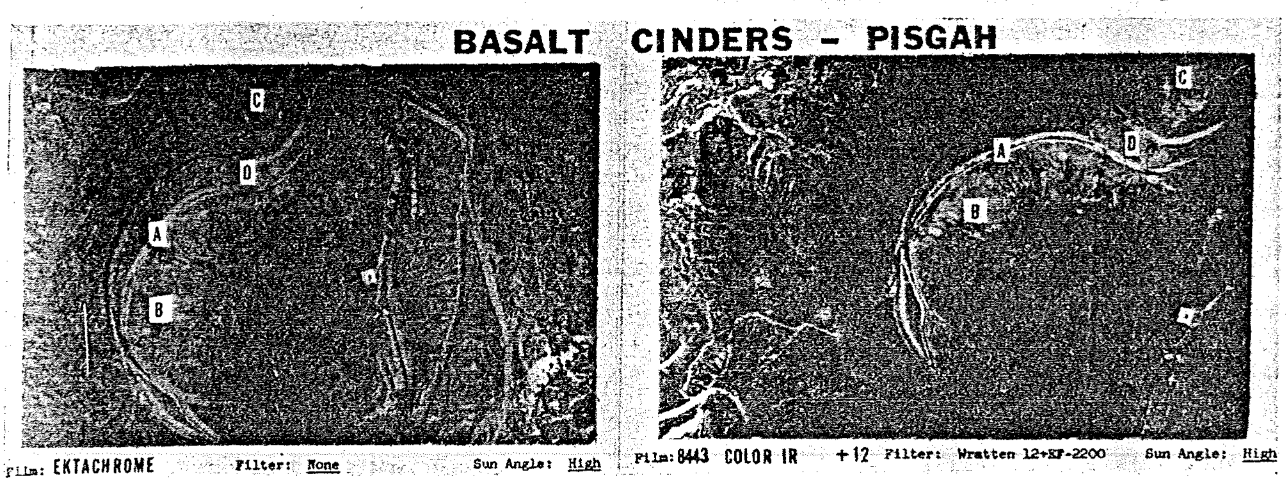

FIG. 7. Comparison between standard color film and infrared color film, as used to accentuate alteration effects in basalt cinders. A comparison between Aerial Ektachrome, and Aerial Infrared Ektachrome (CIR), type 8443, with a #12 filter, over an olivine basalt cinder cone, at Pisgah Crater, California, now presented as black and white copies of the originals. The reddish alteration coatings on the cinders are "transposed" by the CIR film and appeared as bright yellow-green "false colors" at (B,C, and D). The bluish coatings, at (A) appeared as darker green. A parallel example was found with the quartz basalt cinders at Mt. Lassen, California, and with the andesitic volcanics and flows of the Mehrton formation on the top of the Sierra Nevadas, California. Color prints provided by R. N. Colwell, U. C. Berkeley, California, and taken at altitudes around 4,000 ft., and with high sun-angles. B/W copies made with panchromatic film.

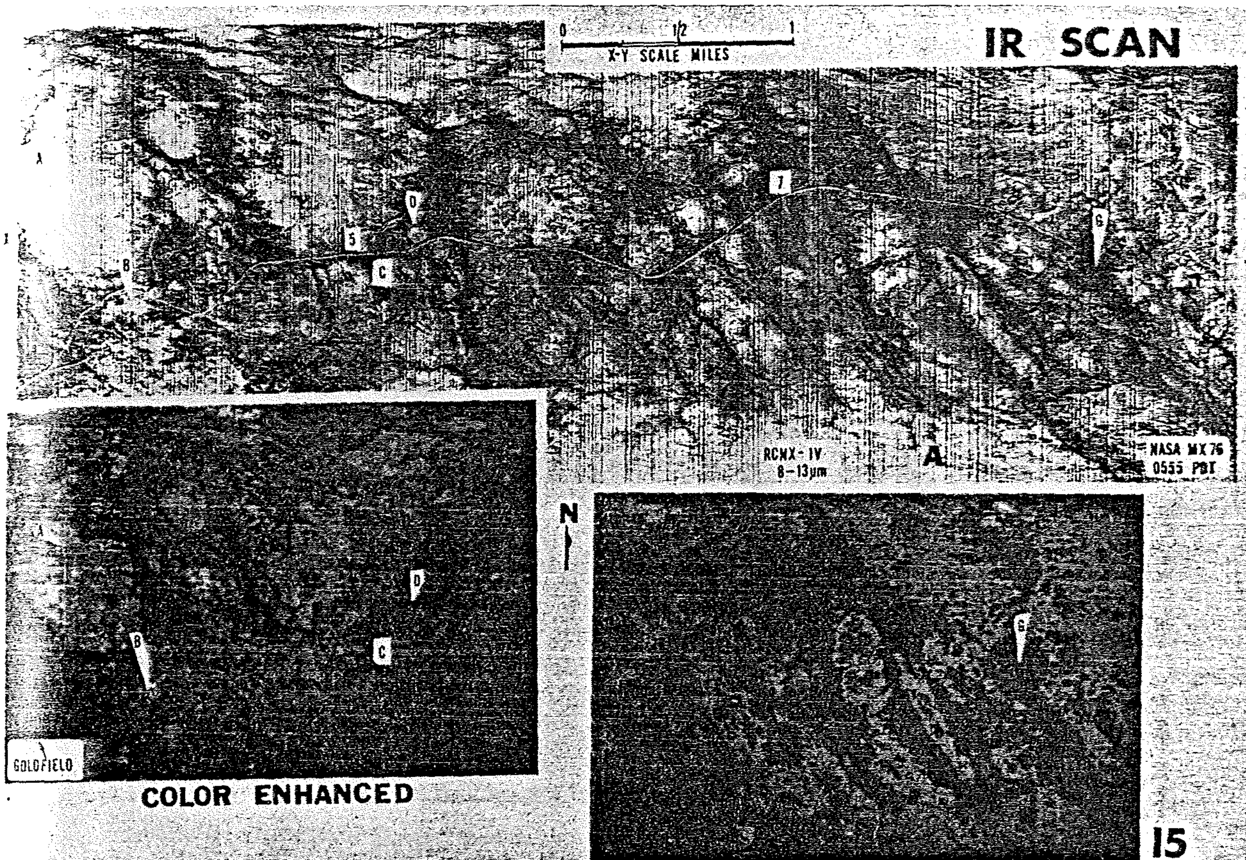

FIG. 8. Infrared Image of Goldfield area, Nevada (after Kilinc and Lyon, 1970). A. *Top*: A long strip (5 miles) of airborne infrared scanning imagery, Reconofax IV, filtered for 8–13μm bandpass, flown July 28, 1967 (NASA Mission 76) at 0555 Pacific Daylight time (approx. 0.5 hours *pre*-dawn). X–Y scale as shown, cross scale is distorted, as with all constant-scan-angle imagery. Old desert mining town of goldfield, Nevada, lies in the extreme SW corner. Roads are all dirt-surfaced with varying degrees of present usage. Central EW road (BCG) is graded-dirt, sand and gravel, and may be followed readily on this image. Its location is obsured in the valley SE of (G) where it passes down a broad slope, shown dark on this positive image (white = hotter, dark = colder). Vertical lines are the raster of scan lines marking each rotation of the scanning mirror in the aircraft. *Solid* rock outcrops are white (A,D), mining dumps (broken rocks and soil) are light grey (B) but with specific and definite shapes, each with a small, square, very black dot marking the mining shaft. Talus and float rock, loose scree slopes, etc. are medium grey (around D), near (C). Alluvium is dark grey to very black due *either* to evaporative cooling from locally higher soil moisture, or cooling from cold air lying in the valleys in the pre-dawn. (C,5,7,G). Rocks are Tertiary volcanics, heavily altered to quartz-alunite assemblages in the mining areas near (B). Topographic relief is moderate (200–400 feet) across the entire area, with elevations of about 5,800 feet above sea level. Localities are Morena Ridge (A), Central mining area (B), Banner Valley (C,5,D). Geological significance of this image lies in the *marked rectangular grid of darker areas.* These linear features are found to be coincident often with the faulting and joints in the volcanics, as mapped by R. Ashley (USGS). Many more can be found by this technique than have been mapped on the ground in three field seasons. This forms an excellent tool to guide the field geologist in his search for fracture intersections, which may be used as ore guides in this mining district. Total temperatures spread, black-grey-to-white would be about 2° to 5° C. B. *Lower Set*: Black and white copies of color enhanced prints of the same positive thermal images, used as transparencies and electronically modified, using the Philco-Ford process (Ross, 1969). The settings used were developed to enhance the darker (cold) areas as black, while originally grey-green, red, and turquoise-blue contours indicated increasing temperature (brighter white) on the original thermal image. Localities are as on the original image, above.

Hydrocarbons

The first two requirements for accumulation of hydrocarbons—source rocks and reservoir rocks—may be determined by aerial mapping using sensors described above under General Geology. Rock distribution maps may also provide information leading to stratigraphic traps. For surface expression of structures which may trap hydrocarbons, LSAP, SLAR and infrared scanners (Fig. 10) will prove most effective.

Ground Water

Surface hydrogeologic features may be mapped by any of the imaging techniques already described. Subtle drainage features may be enhanced on LSAP, SLAR or infrared scan imagery. The latter instrument is particularly useful when there are expected soil moisture variations such as occur along intermittent streams, spring and seepage areas, and uphill of high-angle faults (Figs. 6, 8). Again, it is important that the thermal characteristics of the

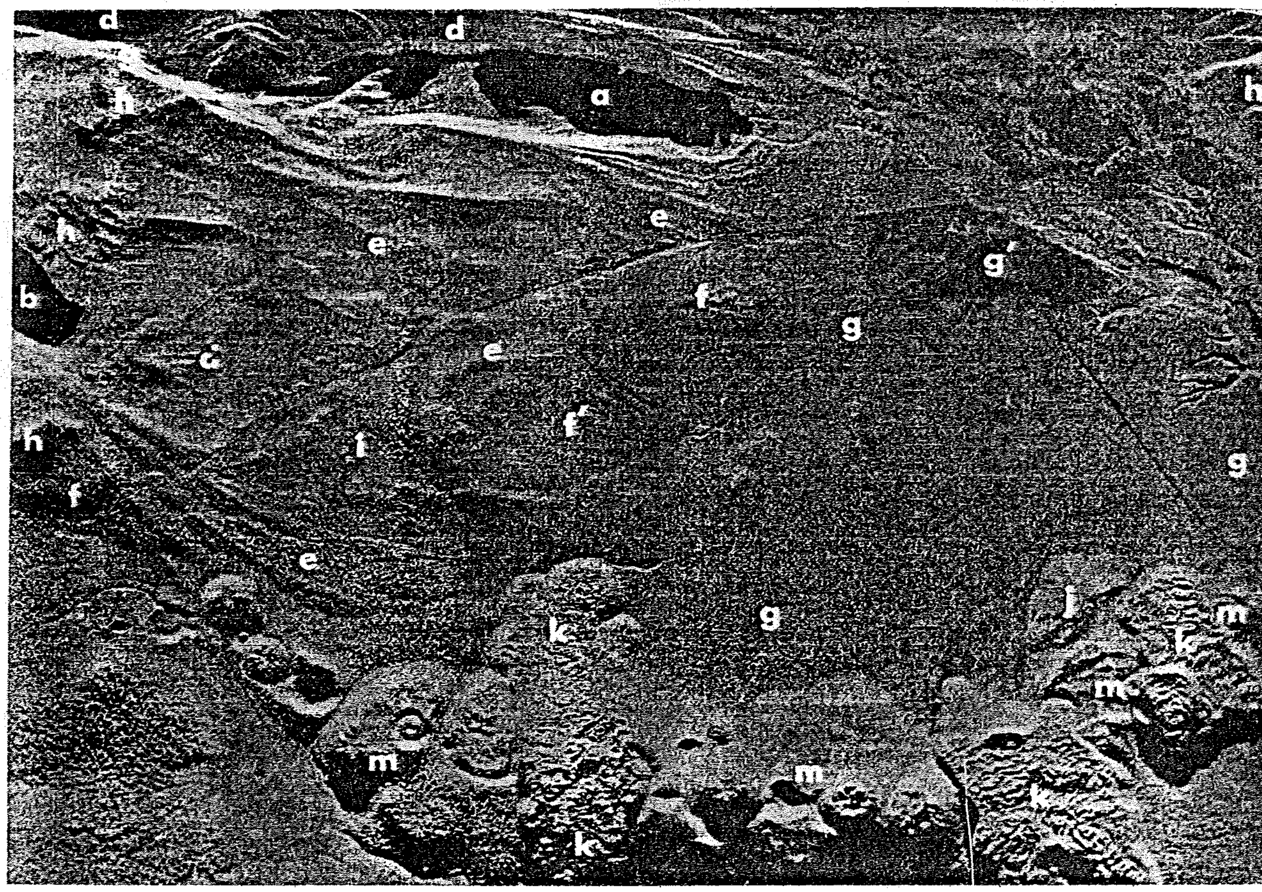

FIG. 9. Side looking, K-band radar (SLAR) imagery at Mono Craters, California. Like-polarized, K-band imagery from Westinghouse AN/APQ-97 radar set. Coarse glacial tills are distinguished from alluvial deposits and from exposures of bedrock. In some cases, glacial tills of different ages may be differentiated. Note also the ability to discriminate rhyolite flows from domes in the Mono Craters. Illustrations from negatives provided by CRES, U. of Kansas, with further annotations by present authors.

(a) Grant Lake
(b) June Lake
(B) Mesozoic intrusives
(d) Till of Tioga Glaciation (Q_{ti})
(e) Till of Tahoe Glaciation (Q_{ta})
(f) Bishop Tuff (ignimbrite) (Q_{bt})
(f′) Basalt with thin pumice cover
(g) Alluvium and pumice sand (Q_{al})
(g′) Cleared fields
(h) Basement of Paleozoic metasediments
(i) Basalt (Q_b)
(j) Andesite (Q_{am})
(k) Rhyolite flows (Q_{rf})
(m) Rhyolite domes (Q_r)

surface soils above possible aquifers be studied in order to maximize the utility of resulting imagery. For example, when a dry sand is moistened, its thermal diffusivity (α) is increased because water has a higher thermal conductivity (K) than the air it displaces (see above, footnote). Therefore, on post-sundown imagery, such areas would tend to image cool (dark). But if the water content were high enough (about 15% or higher), then the high specific heat of the added water would more than offset the conductivity rise, with the result that the same imagery of the same sand would now show it to be relatively warm (light toned).

Springs can be readily detected using an infrared scanner, because they represent convective heat transfer to the surface (as opposed to conductive transfer from oxidizing ores or radioactive decay). Because normal ground water has less of a temperature range than surface water, there will always be times of the day or year when infrared imagery will show effluent ground water into streams and lakes and along coastlines (Lee, 1969). Ice-free reaches of perennial streams, indicative of ground water discharge, are readily detected, as are ground surface icings.

Vegetation, again, can be a good surface indicator of ground water. The distribution of plant species can indicate the presence of water and in some cases permit estimation of the depth to the water table. That plants are indicators of water quality is well known. It remains then to identify these species; rapidly and over large areas. Photographic methods offer this ability (Fig. 11).

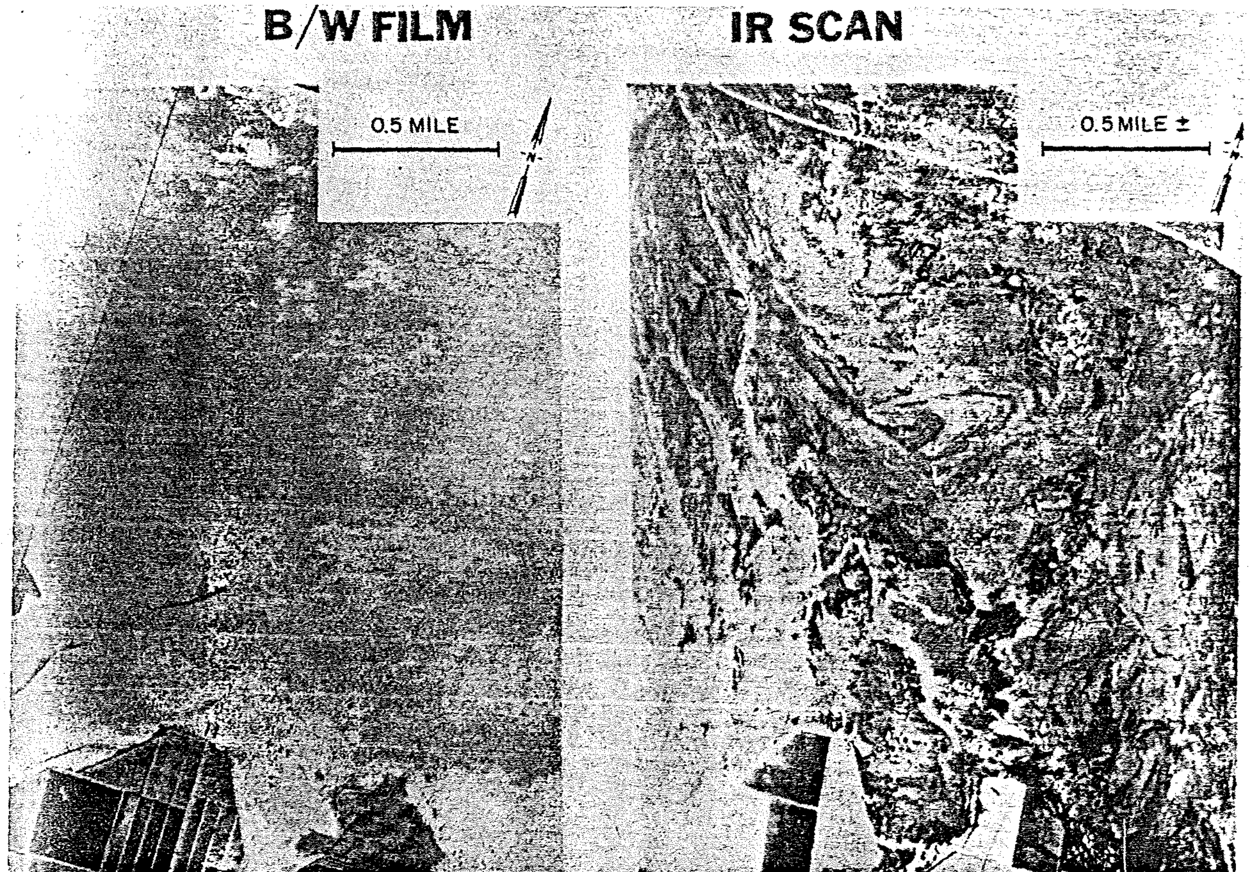

Fig. 10. Black and white aerial photography and infrared imagery compared (after Sabins, 1966). *Left*: Conventional black and white aerial photography flown May 5, 1953 for the U. S. Geological Survey, of an area 15 miles SSE of the Salton Sea in Southern California, in the desert immediately bordering the irrigated regions of the Imperial Valley (dark at lower edge). Scales as shown. *Right*: Infrared scanner image (positive, white = hot) flown by H. R. B. Singer, Sept. 1965, pre-dawn, using a Reconofax IV, filtered for 8–13 μm bandpass. Superstition Hills fault traverses the image from upper left to lower right, transecting the anticlinal structure in the center of the image, both revealed only on the thermal infrared imagery. Ground checking revealed that the thin desert soils here have been removed by the strong prevailing winds, and that in the exhumed structure the beds have a vertical relief of 4 to 6 inches. Surface thermal differences between the sandstones (whiter) and the interbedded shales (darker) have been measured at 1° to 2° C., at 4 to 5 AM, pre-dawn. Trees and shrubs are warmest, at about 5° to 10° C above the coldest soils. (Illustration by kind permission of Geological Society of America, and F. Sabins).

Ground water in permafrost areas presents special problems, but the later discussions on permafrost will apply as well to a search for ground water in these areas.

Geothermal Energy

Potential geothermal energy sites are a natural application for infrared scanners because there is generally convective or advective heat transfer at the surface. On example of thermal imagery near the Mono Craters in California clearly detected a warm spring that was flowing less than one gallon per minute (Lee, 1969). Similar studies of hot springs and warm ground due to convection and liberated heat of condensation in Yellowstone National Park have been published (Miller, 1966). Fumaroles image well also, as do thermal patterns associated with recent and active volcanism (Fig. 12). Because these anomalous areas are always relatively warm, the optimum time for thermal surveys is pre-dawn in winter time.

Soil and rock discolorations are common around warm vents, and vegetation anomalies certainly occur (Miller, 1966).

Permafrost

Because 85 percent of Alaska is to some extent underlain by permafrost, this must rank as one of the most important problems in the development of the State. Engineering geology sites for buildings, airfields, railroads and highways must be evaluated before construction can be planned. It is perhaps in this area that remote sensing techniques can be of the most immediate use.

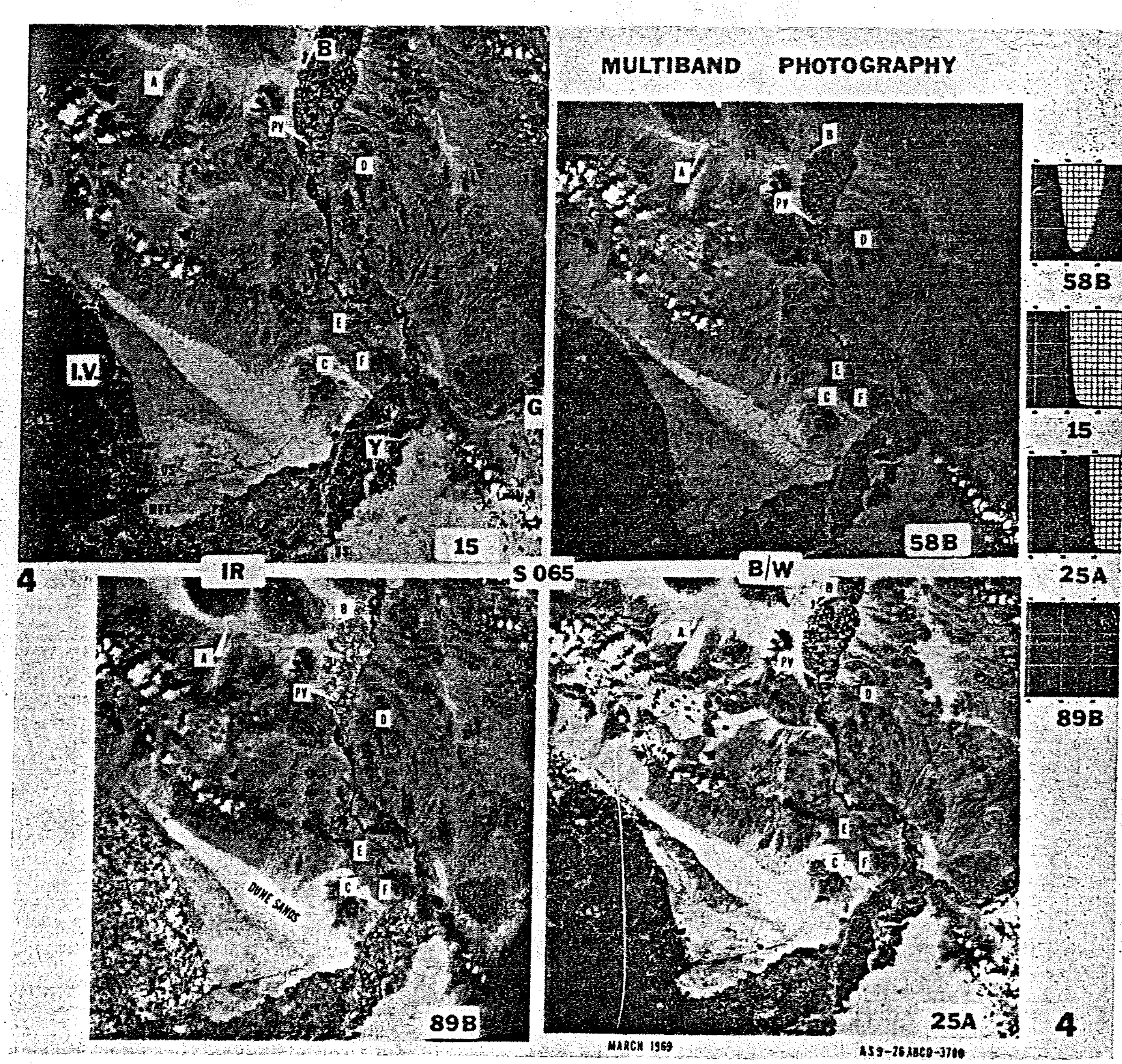

FIG. 11. Multiband photography from space (Apollo 9) over Blythe, California and Yuma, Arizona. Four photographs in the visible and near-infrared, taken in the S065 experiment, on Apollo 9, March 1969. Bands are shown by their filter designations, as follows: Band A; Color IR plus #15 filter, Band B; B/W plus #58B (Green), Band C; B/W IR plus #89B filter, Band D; B/W plus #25A (Red) filter. Bandpass details are shown on the associated graphs. Frames are AS9-26-A, B, C, D-3700 (NASA). Annotated localities of interest are:

A. Playa (Ford Lake) on Highway 60, seen more clearly on 58B band.
B. Township of Blythe, California, on the Colorado River. Arrow points toward the airfield to the left (West), seen best on 58B and 25A bands.
C. Cargo Muchacho Mtns. (see text)
D. Northern end of Trigo Mtns. in Yuma Test Station., Mojave Peak is just to SE of (D).
E,F. Two areas in the Chocolate Mtns., which run up to and off left top of pictures. (see text)
G. Gila River, Arizona.
I.V. Imperial Valley, California, a rich farming area, heavily irrigated from the Colorado River.
P.V. Palo Verde, California, town and irrigation area.
Y. Yuma, Arizona, town and irrigation area. East bank of Colorado river here is USA; West is in Mexico.

Illustrations provided by NASA, with further annotation by present authors.

While, with the exception of pingos, there does not seem to be any single surface feature which alone is an infallible indicator of permafrost, there are many surface phenomena that strongly suggest its presence and which, taken collectively, leave little doubt as to the occurrence of permanently frozen ground. Fortunately, these features lend themselves to identification by remote sensing methods.

Polygonal ground, commonly ascribed to the action of ice wedges, generally indicates a permafrost table near the surface. These patterns are recognizable on conventional air photos, and infrared photography

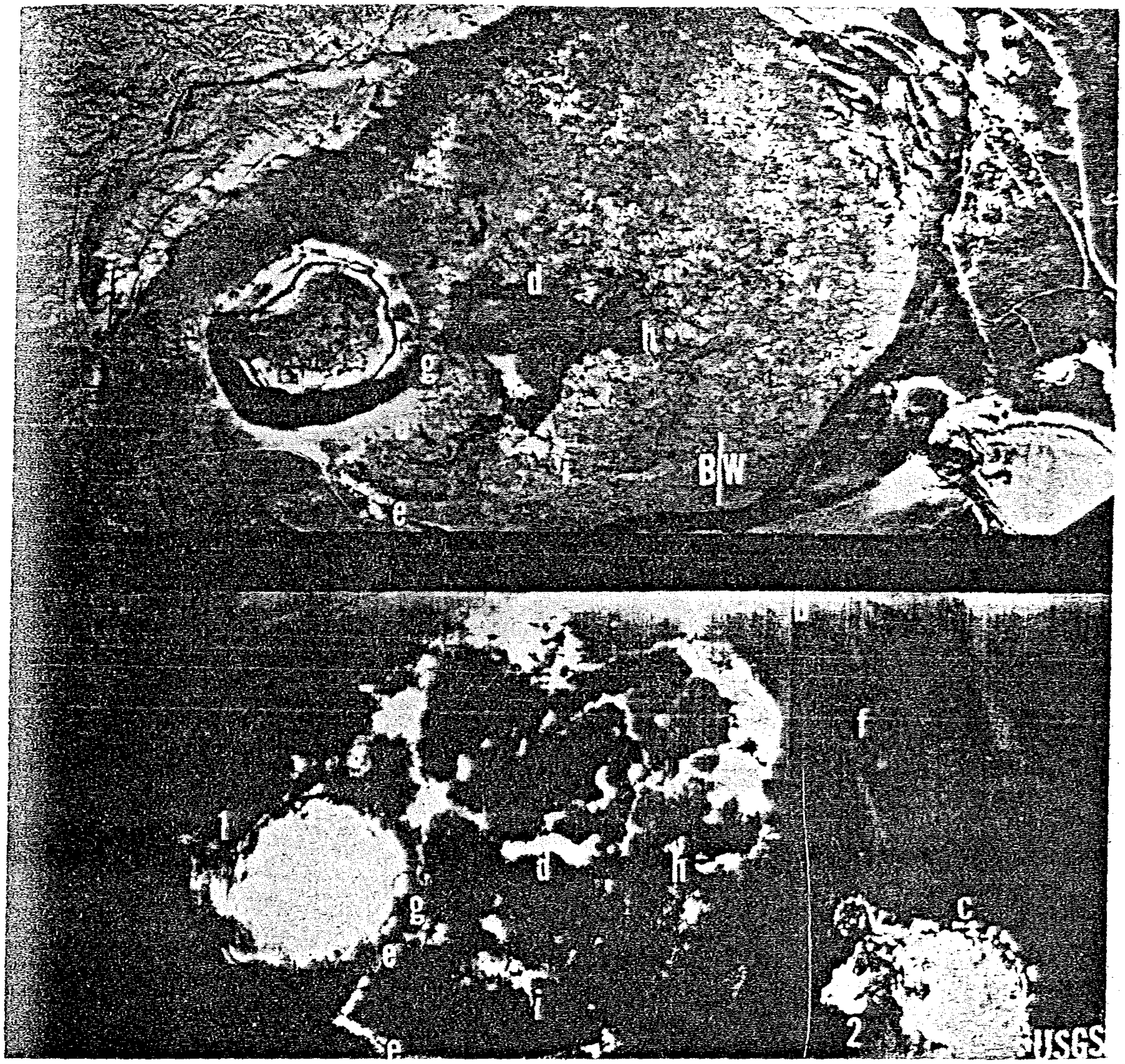

FIG. 12. Comparison between B/W photography and thermal infrared imagery of Kilauea Summit, Hawaii (after Fischer et al, 1964). *Top*: Black and white photograph of the summit of Kilauea volcano. High sun-angle used, probably the 53° sun-angle print of Figure 5. Bottom: Thermal image (white = hot) produced by a line-scanner operating in the 4.5 to 5.5 μm bandpass flying over the same area at 0702 hours on Jan. 28, 1964 (0.5 hours *after* sunrise). Generally whiter areas on photograph agree with white (hot) areas on thermal image. Compare annotated localities (c, e-e, f,g,h, and i) on both prints, but notice carefully that dark and light areas are not always the same on photograph and infrared image. In particular, the thermal patterns on the floor of Kilauea Crater do not conform to the boundaries of historic flows and to mapped fractures (e.g. the fracture zone from g to h). The overall thermal pattern is suggestive of a series of convective cells. Illustrations from USGS, with further annotation by present authors.

1. Halemaumau Crater (active 1961 and present)
2. Kilauea Iki Crater (spectacular fountain eruptions of 1959)

a. hot spot in lava flows of 1919
b. numerous slump blocks along crater rim
c. localized fumarolic activity
d. lava flows of 1954 (dark in photo)
e. fault traces (?)
f. one of series of concentric down-to-center faults (Waldron Ledge)
g–h. fracture zone from which the 1954 lava flows emanated

would only increase resolution and range because of its greater haze penetration. Stereoscopic photography is helpful in determining whether the polygon centers are raised or depressed, which in turn yields information on the nature of the soil and its drainage. Where these patterns are weakly developed, LSAP or SLAR may give enhanced definition. Thermal imagery flown during the seasonal thaw could readily distinguish thawed ground from ice wedges. Patterned rocks, thermokarst features,

TABLE 2

Status of Electromagnetic Remote Sensors from Viewpoint of Economic Geology*

Sensor (in Priority)	Application in Economic Geology	Operating Mode		Rationale
		Spacecraft	Aircraft	
I. Photography (0.4–1.0 μ)	Structural geology (lineaments, faults, folds, etc)	Best	—	Affords essential synoptic view and orthogonal presentation.
II. Radar	Structural geology (lineaments, faults, folds, etc)	—	Best	It is assumed that resolutions from aircraft will be finer than those from spacecraft. Swath widths for both are comparable.
III. Infrared imaging	A. *Convective* mass transfer at surface (volcanoes, geothermal areas)	—	Best	Areas are small, localized, and/or need repeated monitoring.
	B. *Conductive* heat transfer to surface			
	1. Landslides, oxidizing orebodies	—	Best	Areas are small and localized near lineaments or intersections of lineaments.
	2. Outcrop maps (soil/rock interfaces, physical composition)	—	Best	Diurnal rate of change of ΔT is essential. Not achievable except from geosynchronous orbit.
Spectroradiometric	Rock and soil composition (chemical-mineralogical)	—	Best	Spectrometer field of view is fixed by available energy, and smallest ground resolution is essential. Spacecraft smear is higher than with aircraft.
IV. Ultraviolet	Rock-type discrimination	—	Best	Increasing altitude cuts off useful lower wavelengths.
V. Microwave	Ground penetration ability	?	Best	Field of view wider than acceptable except when used in aircraft. Needs R & D.

* Herein defined to include engineering geology; but excludes hydrology and oceanography.

beaded drainage and pingos, or hydrolaccoliths, can also be enhanced by LSAP or SLAR, and the patterned rocks may lend themselves especially well to striking returns from SLAR.

Vegetation, once again, can be highly indicative, not only of the presence of permafrost, but of the expected depth to the permafrost table. Trees that have very shallow root systems, such as larch and black spruce, can tolerate a permafrost table within a very few feet of the surface, whereas tall willows and mature aspens, which have deep root systems, indicate deep or absent permafrost. Hopkins and others (1955) have tabulated vegetation assemblages that are widespread in Alaska along with their associated minimum depth to permafrost. It should be a relatively easy matter to catalog reflectance spectra of these common trees as a prelude to flying wide area coverage with multiband photography or multiband scanners.

Status Summary for Sensor Techniques

In analyzing the present status (or degree of usefulness) of various techniques for geological exploration of the earth, a tabulation with a priority listing was prepared. This is reproduced here as Table 2 (from Nat. Acad. Sci., 1969, p. 36).

Photography and Radar

The most useful techniques are listed as photography (in the visible near-infrared) and side-looking radar. Detailed study of this table is recommended, as it seeks to show the rationale for the relative sequences of selection.

Thermal Infrared

Third in the listing is thermal infrared. This is at its best in the detection of *convective or advective* heat transfer at the surface; for example, the detection of volcanoes and other geothermal phenomena, or hot and cold springs in lakes and oceans. Of diminished success is thermal infrared when used for studies of conductive heat transfer to the surface.

Ultraviolet and Gamma Ray

Ultraviolet reflectance or emission (fluorescence) is markedly attenuated by the atmosphere, as are gamma-ray measurements (used for the detection of K, U, and Th isotopes and daughter elements). Low altitude (400 feet above ground) gamma-ray measurements for K^{40} are useful indicators for potassium-enrichment, a characteristic of porphyry copper deposits. A suitable flight could also involve simultaneous low-level aero-magnetic measurements to yield a powerful cross-relationship in the data.

Microwave

Microwave emission techniques, though intrinsically attractive because of deeper penetration abilities than infrared, suffer because the low energies available dictate wide resolution cells (of several degrees angle) for data collection.

Conclusions

Review

This paper has attempted to emphasize the following points, as specifically applied to remote sensing for mineral resources:

a. Photographic film is now and will still be, the prime sensor. This is mainly because of rapid data collection over wide areas and the natural inclination of earth scientists towards imaged-, rather than non-imaged data. The geometric similarity of the photograph to the natural terrain forms the basis for this opinion.

b. The uses of color film (Ektachrome and Aero-Neg), and particularly color infrared film (CIR), are still being developed, even from low-to-medium-flying aircraft.

c. Low sun-angle illumination is a much-neglected photographic technique of great potential value to the geologist. (Clearly this has been a way of life in Alaska, but it is often neglected at lower latitudes).

d. Thermal imagery should be flown at low altitudes (1,000–5,000 feet). It should be flown repeatedly, under several meteorological conditions and seasons, and at several altitudes. Foreknowledge of the thermal characteristics of surface materials will greatly improve efficiency. Most applications for economic geology will be for coverage of areas 5–20 square miles in size (mining and geothermal power). For such applications spacecraft would not prove to be the best vehicle.

e. Most remote sensing surveys should use light aircraft at times and in seasons which best amplify the contrasts (either tonal or structural) which are sought. Remote sensing should be a small-scale *personal* effort, strongly involving the geologist. He should have had sensor training, but only after a strong grounding in photogeological techniques. *He must direct the program, define its objectives, and personally be present during the data-gathering.* Rapid availability of final data is essential, so that corrections in flying times and techniques can be made to achieve better the objectives.

f. One theme has been belabored in the above discussion, and it will be repeated once again. The most outstanding single requirement for effective use of remote sensors is the definition of those *surface* phenomena which (1) indicate the presence of the target sought and (2) lend themselves to detection from aircraft or spacecraft. Such definition requires the combination of geologic knowledge and familiarity with remote sensing instruments.

Prognosis

1. The camera will continue to be a prime instrument, but as data enhancement becomes a more commonly used processing step, tape recorded data from TV or Vidicon units will replace the camera for these tasks.
2. Optical-mechanical scanners with their wide range of wavelength capabilities (reflective optics) will be modified to be many-channel systems, simultaneously sensing a variety of bands with complete spatial (and temporal) register. Computer analysis of image-forming data will be common, and often only the X-Y locations of specific spectrum-matching tasks will be the final data output.
3. Radar will be developed towards longer wavelengths, for deeper penetration of vegetation and/or soils. Microwave temperatures at depths of -30 cm or so will become useful to delineate geothermal contours below the input of the diurnal solar wave.
4. Light aircraft, flying at low-to-medium heights, will be the mainstay of local programs. A strong development will become evident for several instruments to be flown at a time,

mixing deeper-penetrating EM and magnetic methods with camera and thermal sensors.

5. Finally, we are witnessing a boom period somewhat like that during the introduction of B/W aerial photography after World War II. There will be many applications where the methods do not work satisfactorily. From careful analysis of these failures and the few good successes will come the most useful tools for mineral exploration since the airplane.

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