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Infrared Imagery and Geologic Aspects

Structural and stratigraphic interpretations can be made from nighttime infrared scanner imagery in the Indio Hills, Calif.

(Abstract on next page)

Introduction

Location and Geologic Setting

The Indio Hills are a low, narrow, northwest-trending ridge located in the eastern Coachella Valley, Riverside County, California (see Figure 1). The hills are twenty miles long, up to four miles wide, and rise to maximum elevations of 1,600 to 1,700 feet. A narrow valley, approximately 1,000 feet in elevation, separates the hills from the Little San Bernardino Mountains to the northeast. The broad Coachella Valley on the southwest side of the hills is only a few hundred feet above sea level. There are no permanent streams in this hot, dry climate, but many dry washes and gravel-filled stream channels. The landforms are rugged, and much bedrock is exposed in the hills.

Bedrock in the Indio Hills consists of folded and faulted clastic sedimentary rocks of late Tertiary and Quaternary age. The adjacent valleys are covered with undeformed sand and gravel of Recent age. Geologic structure is dominated by the San Andreas fault zone, which extends through the length of the hills. Both vertical and right lateral movements have occurred along the faults. Recent earthquakes (Allen and others, 1965) and fresh fault scarps demonstrate that the faults are still active.

This combination of dry climate, good outcrops, and varied geology makes the Indio Hills an excellent site for evaluating the geologic aspects of infrared imagery.

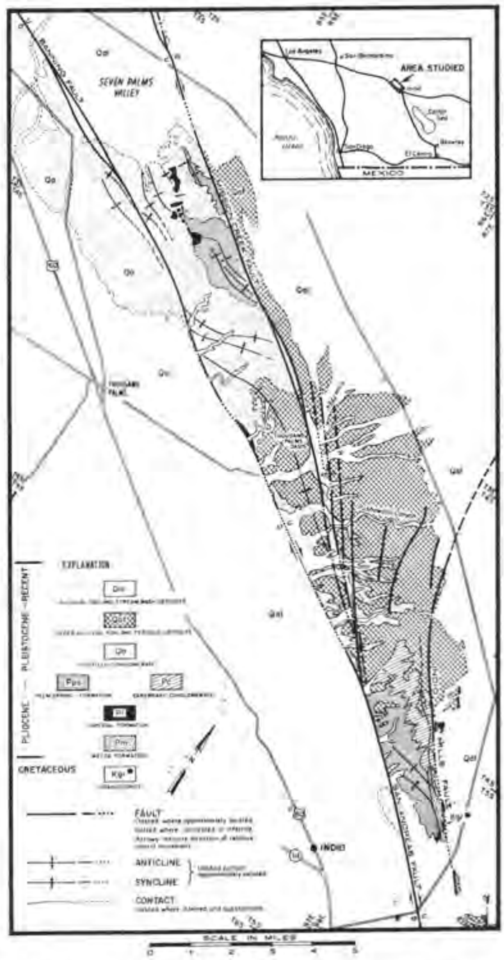

Fig. 1. Geologic ap of Indio Hills, Riverside County, California. From Farrell (1964, Pl. 3-B).

Methods

Nighttime infrared scanner imagery was flown in August, 1961 and declassified in 1964. Flights were made at high and low altitudes, oriented parallel with the trend of the Indio Hills. This was in the 8 to 14 micron bandwidth.

Contact prints from the original 70 mm. film negatives were used for interpretation and are reproduced in this report as Figures 2 and 3. On the prints, light areas represent relatively warm radiometric temperatures, and dark areas relatively cool temperatures. Because this is an interpretative report, the darker-appearing imagery will be referred to as "cooler" and the lighter imagery as "warmer." It is understood that emissivity

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variations as well as temperature variations control the radiometric response. For information on the principles of infrared radiometry the reader is referred to Simon (1966); Parker and Wolff (1965) have described the operation of infrared scanning devices. A conventional aerial photograph of the south end of the hills (Figure 4) is shown for comparison with the imagery.

One strip of higher altitude imagery extends the length of the Indio Hills from northwest to southeast, and is reproduced on Figure 2. In order to fit the page, the strip was cut into two sections that join as indicated. Lower altitude imagery is reproduced on Figure 3. The segments were taken from longer strips and were selected to illustrate typical features. These illustrations are contact prints that have not been dodged or enhanced. The irregular borders were caused by the roll-compensation device in the scanner.

Our objective was to correlate the imagery with the geologic features of the Indio Hills, using geologic maps, aerial photographs, and field observations in the interpretation. Stratigraphy and structure are the two major geologic aspects visible on the imagery. These are discussed in the following sections.

ACKNOWLEDGMENTS

The writer is grateful to the management of Chevron Research Company and Standard Oil Company of California—Western Operations Incorporated for permission to present this paper; to Professor R. J. P. Lyon of Stanford University, who made a radiometer available and discussed the results; and Mr. Eugene Borax of Union Oil Company, who accompanied the writer on a field trip to the area and discussed various problems with him. The figures were drafted by Mr. J. C. Keeser.

ABSTRACT: *Structural and stratigraphic interpretations can be made from nighttime infrared scanner imagery in the Indio Hills. The younger, undeformed alluvium covering the valleys images distinctly cooler than the older, deformed sedimentary bedrock of the hills. The bedrock consists of two distinctly different stratigraphic-radiometric units. The poorly stratified unit is relatively featureless on the imagery, whereas the well stratified unit has a distinct pattern of alternating warmer and cooler bands that correspond to outcrops of sandstone and siltstone beds respectively. A concealed trace of the San Andreas fault is revealed on the imagery by a cold anomaly apparently related to blockage of groundwater. Other faults and folds are imaged by offsets and strike changes in the patterns of the stratigraphic-radiometric units.*

STRATIGRAPHY AND RADIOMETRIC EXPRESSION

The rock formations are shown on the geologic map (Figure 1) and stratigraphic section (Figure 5). A small outcrop of Cretaceous granodiorite occurs at the southeast end of the Indio Hills, but is too small for recognition on the imagery or aerial photographs. All of the other units are unconsolidated to moderately consolidated deposits of shale, sandstone, and conglomerate that range in age from Pliocene to Recent. For purposes of imagery interpretation, the seven stratigraphic units are placed in three major groups, based on stratigraphy and radiometric expression. These stratigraphic-radiometric units are: alluvium; poorly stratified bedrock; and well stratified bedrock (Figure

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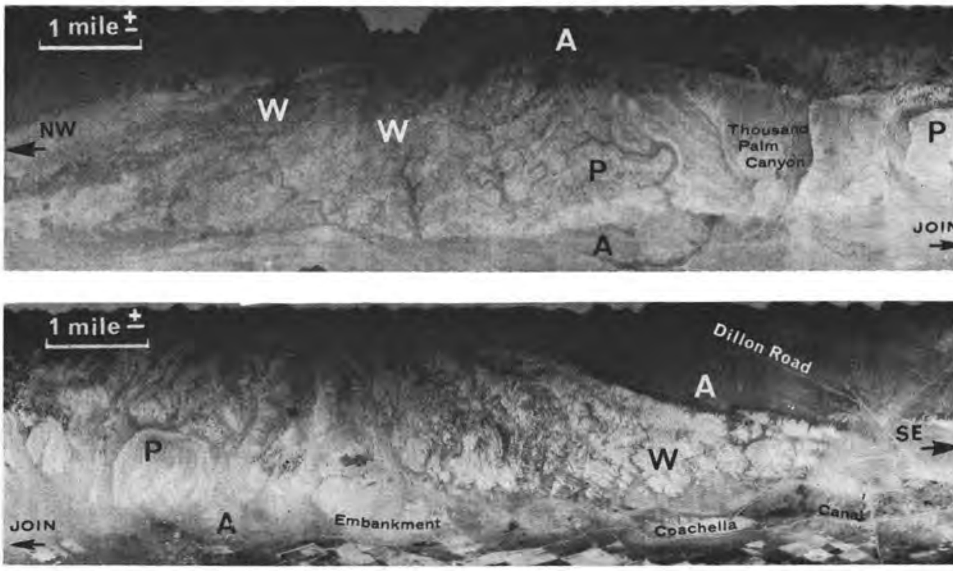

FIG. 2. Higher altitude imagery. This is a continuous strip that joins as indicated. Symbols for stratigraphic-radiometric units are: *A*—alluvium; *P*—poorly stratified bedrock; *W*—well stratified bedrock.

5). Distribution of the units is shown on the radiometric map of Figure 6.

ALLUVIUM

These are the youngest sediments in the area and consist of alluvial fan and stream deposits forming the surface material of the valleys adjacent to the Indio Hills. Unconsolidated sand and gravel, plus some dune sand are the principal components. The surface is cut by steep-sided dry washes that radiate out from the mouths of canyons in the Indio Hills. Scattered, low-growing desert shrubs and a few small trees are the only vegetation.

On the infrared scanner imagery (Figures

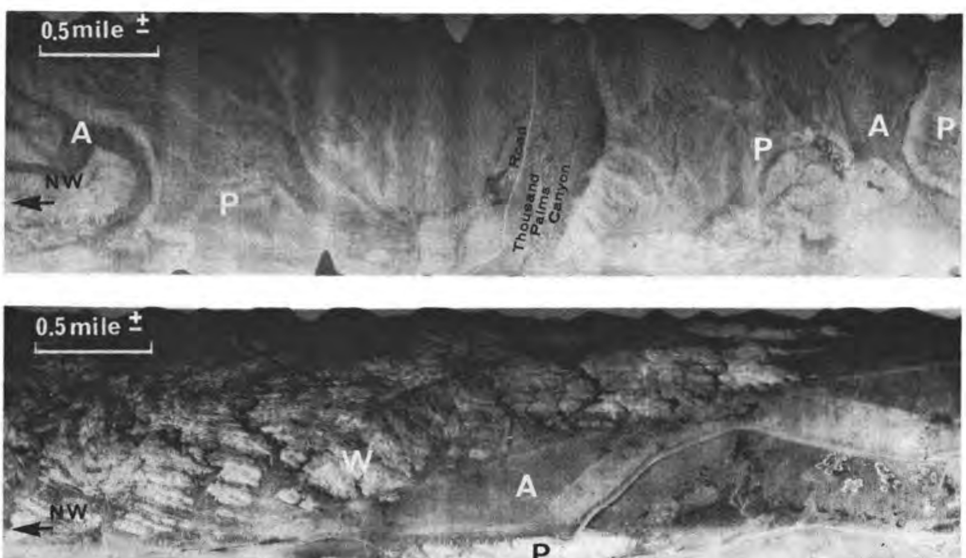

FIG. 3. Lower altitude imagery. The upper strip shows typical appearance of poorly stratified bedrock *P* and alluvium *A* in the vicinity of Thousand Palms Canyon. The lower strip shows the southeast end of Indio Hills with prominent folds in well stratified bedrock *W*. Compare with Figure 4 for the identification of the other features.

FIG. 4. Vertical aerial photograph of the southeast end of Indio Hills. Compare with the lower strips of imagery in Figures 2 and 3. See Figure 2 for the explanation of the stratigraphic-radiometric units.

2 and 3), the most striking characteristic of the alluvium is that it is cooler than the bedrock of the hills. This radiometric difference is not due to a difference in rock composition for the alluvium was derived from the bedrock. The greater porosity of the unconsolidated alluvium may explain why it appears cooler than the more consolidated bedrock. There is also a difference in groundwater distribution. The uplifted bedrock of the hills is dewatered, whereas the water table is less than a few hundred feet below the surface in the alluvium-covered valleys (Farrell, 1964, p. 32, Pl. 8).

On Figure 2, it appears that the alluvium on the northeast side of the hills is cooler than on the southwest side. These areas are near the edges of the imagery strips, however,

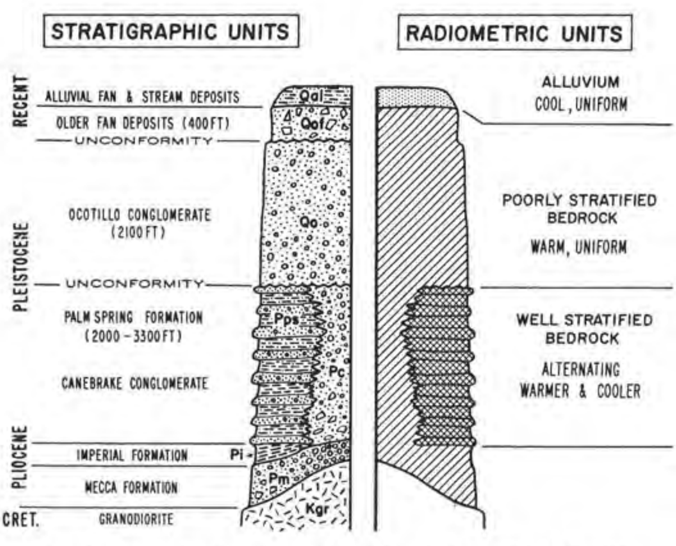

FIG. 5. Generalized stratigraphic column (from Dibblee, 1954; Farrell 1964) and radiometric units for Indio Hills.

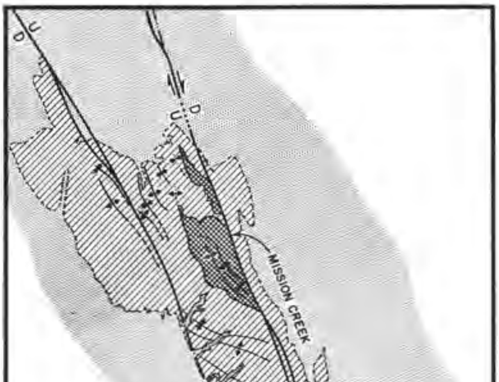

FIG. 6. Map of stratigraphic-radiometric units for Indio Hills.

so the apparent differences may be instrumental rather than real.

Some of the larger gravel-floored dry washes that cut the alluvium and bedrock show up as very dark, irregular lines that are distinctly cooler than adjacent areas. Underflow of water in the gravel may cause this cooler pattern. The small tributaries without much gravel have an anastomosing pattern that is warmer than the bedrock.

The alluvium appears distinctly warmer along the northeast margin of the earthen diversion embankment that protects the Coachella Canal at the southeast end of the hills (Figure 3, lower strip). Field inspection showed that this warmer area corresponded to the shallow excavation that supplied material for the embankment. Patches of much cooler alluvium occur in the area southwest of the embankment. This coincides with the trace of the San Andreas fault and is discussed later.

The scattered trees and shrubs are warmer than the alluvial surface upon which they grow. A peculiar vegetation pattern occurs at the southeast end of the hills, between the Coachella Canal and the embankment (Figure 3, lower strip). These are irregular patches with a very warm rim and cool center. A field check showed that these were slumps of desert shrubs that had grown outward from a center, leaving dead vegetation surrounded by live plants that imaged warm.

BEDROCK

The bedrock of the Indio Hills consists of moderately to poorly consolidated shale, sandstone, and gravel that are faulted and folded. The bedrock consists of six mappable formations shown on the geologic map (Figure 1), but these can be grouped into two subdivisions on the basis of stratification and the well stratified bedrock (Figure 5).

POORLY STRATIFIED BEDROCK

This unit includes all the strata of the Indio Hills, except for the Palm Spring Formation (see Figure 5). The following formations are included: Mecca Formation, Imperial Formation, Canebrake Conglomerate, Ocotillo Conglomerate, and older fan deposits. The total thickness of these units is estimated at greater than 6,000 feet (Dibblee, 1954, p. 24; Farrell, 1964). Stratification, or bedding, is poorly developed and obscure both on aerial photographs and ground level observations. The topographic expression of these units is a relatively uniform slope, cut

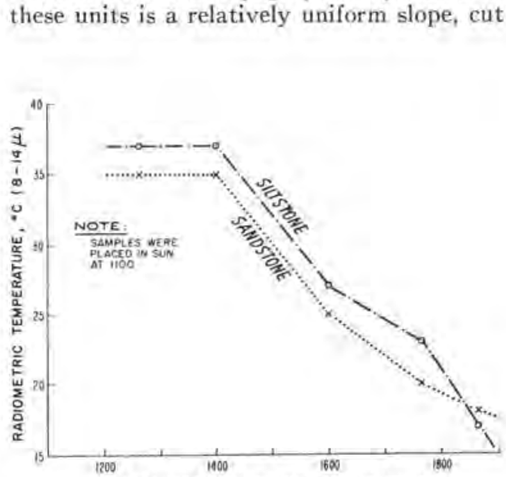

FIG. 7. Diurnal variations in radiometric temperature of sandstone and siltstone from Palm Spring Formation.

by steep-sided gullies. The slopes are covered with gravel weathered from the bedrock.

Except for the Imperial Formation, all of the units are nonmarine and consist of coarse, silty conglomerate and sandstone, in various shades of gray, brown, and tan. There are minor interbeds of green and brown silt and clay. The rounded to angular cobbles and boulders consist of granitic and metamorphic rock fragments that were probably derived from the crystalline rocks of the Little San Bernardino Mountains to the northeast. The coarse texture, poor sorting, and lack of well developed stratification indicate that the sediments were rapidly deposited.

The Imperial Formation is only a few hundred feet thick and consists of yellow-weathering marine clay. Stratification is poorly expressed on the outcrops and the Imperial Formation is not distinguishable on the imagery from the rest of the poorly stratified unit. This may be due to the small size of the Imperial outcrops and to their cover of gravel eroded from adjacent conglomerate units.

In Figure 3, the upper strip of imagery is from the vicinity of Thousand Palms Canyon and shows the typical expression of the poorly stratified bedrock, which is distinctly warmer than the alluvium. Tonal variations in the bedrock imagery are related to variations in the drainage pattern. The larger, alluvium-floored channels are cooler than the poorly stratified bedrock. Many of the steep bluffs cut into the bedrock are warmer than either the alluvium at their base or the tops of the small mesas. This may be caused by differential rates of heating and cooling related to the different exposures. Also the bluffs are fresher outcrops and lack any of the sparse vegetation and gravel cover of the mesa tops.

Aside from these variations controlled by topography and drainage, the poorly stratified bedrock has a relatively uniform and monotonous radiometric expression. This is related to the lack of any pronounced lithologic variation in this thick sequence of conglomerate and sandstone.

WELL STRATIFIED BEDROCK

This unit consists of the Palm Spring Formation, which ranges from 2,000 to 3,300 feet in thickness. In contrast to the poorly stratified unit, the Palm Spring consists of distinct, alternating beds of sandstone and siltstone up to 40 feet thick. It weathers to a ridge and slope topography formed by the more resistant sandstones and the intervening, nonresistant siltstones. The sandstones are actually friable, but in this arid climate they are relatively resistant to erosion. The white- to tan-weathering sandstones are medium- to coarse-grained and are poorly sorted with scattered pebbles and cobbles. The siltstones are dark gray and contain abundant fine-grained mica flakes. In the southeastern Indio Hills the Palm Spring Formation grades laterally northeastward into the Canebrake Conglomerate.

As shown on the radiometric map (Figure 6), the well-stratified unit crops out at the northwest and southeast ends of the Indio Hills. Typical imagery on the lower strip of Figure 3 shows that the unit has a distinctive pattern of alternating warmer (lighter) and cooler (darker) bands. Field checking and comparison with aerial photographs indicated that the warmer radiometric units correspond to the sandstones and the cooler units to the siltstones.

In order to evaluate these radiometric differences, large samples of typical sandstone and siltstone outcrops of the Palm Spring Formation were brought to Fullerton, California. On October 29, beginning at 1,100 PDT, the samples were placed out-of-doors and allowed to warm in the sun. Beginning at 1,230, radiometric temperatures were determined with a Barnes radiometer in the spectral range from 8 to 14 microns. The results are plotted on Figure 7 and may be summarized as follows: during mid-day the siltstone reached a maximum temperature of 37°C and the sandstone 35°C; both units cooled down during the afternoon, with the siltstone remaining a few degrees warmer; apparently there was a thermal cross-over in the early evening, for the siltstone became cooler than the sandstone. This latter condition agrees with the relative temperature of sandstone and siltstone shown on the nighttime infrared imagery. Our radiometric studies are preliminary; we plan to extend them by taking a radiometer to typical outcrops and measuring a complete diurnal cycle in place.

STRUCURAL GEOLOGY AND RADIOMETRIC EXPRESSION

Bedrock of the Indio Hills is complexly folded and cut by faults that have been the site of relatively recent movement. The Mission Creek and Banning faults merge toward the southeast end of the hills, and the name San Andreas fault is then used. The major structural features will be described, together with an analysis of their expression on the infrared imagery.

MISSION CREEK FAULT

At the northwest end of the hills, the Mission Creek fault is marked by a northeast-facing escarpment. The apparent stratigraphic displacement is vertical, with the southwest side uplifted relative to the northeast. Strike-slip movement could also explain these features (Farrell, 1964, p. 36). The fault extends northwest beneath the alluvium of Seven Palms Valley, where hot water wells have been drilled. Surprisingly, there are no infrared anomalies along this portion of the fault.

Where it crosses Thousand Palms Canyon, in the middle of the Indio Hills, the fault trace is marked by an oasis caused by blockage of ground water on the upstream (northeast) side. This blockage and the fault trace are clearly shown on the upper strip of Figure 2 by the very cool (almost black) alluvium on the northeast, adjacent to warm bedrock on the southwest. To the southeast along the fault, there is an alignment of similar, smaller patches of very cool alluvium.

Southeast from the oasis the Mission Creek Creek fault cuts diagonally across to the southwest side of the hills, where it merges with the Banning fault. This diagonal course is marked by aligned canyons and faults. It can be recognized on the imagery by marked differences in drainage pattern expression on opposite sides.

BANNING FAULT

At the northwest end of the Indio Hills, the Banning fault cuts across the northeast flank of Edom Hill. A narrow band of cooler imagery marks this trace. This anomaly could be caused by the fault, but it could also be caused by topographic effects at the dry washes that follow this portion of the fault.

Southeast of Edom Hill the fault follows the southwest margin of the hills, but is covered by alluvium for much of its course. Aside from the contact between warmer bedrock and cooler alluvium, there is little infrared evidence for this portion of the fault.

SAN ANDREAS FAULT

Southeastward from the junction of the Mission Creek and Banning faults, the name San Andreas fault is used. The fault is marked by a southwest-facing linear scarp of bedrock that is also the boundary between the Indio Hills and the alluvium-covered Coachella Valley. It is interesting to note that this scarp and the opposite-facing scarp at the northwest end of the hills are offset about 10 miles in a right-lateral direction along the Mission Creek-San Andreas fault zone. Also, the outcrops of Palm Spring Formation on opposite sides of the fault zone are offset by a similar distance. Dibblee (1954, p. 26) has noted this apparent right-lateral slicing of the hills. Some of the older drainage channels have offsets of several hundred yards along the fault, but the youngest channels have none. Very recent lateral movement has been absent along this stretch. Ground water seeps along the bedrock scarp are marked by groves of palm trees and crusts of white mineral deposits from the evaporating ground water.

The scarp and fault are expressed on the imagery by the contrast between warmer bedrock and cooler alluvium. The ground water seepage is only faintly and uncertainly imaged as slightly cooler patches along the scarp. The white mineral crusts may have a masking effect on the imagery expression, as suggested by Mr. T. R. Ory (personal communication).

Southeast from the Indio Hills, the San Andreas fault passes on the east side of the outlying hill of Ocotillo Conglomerate and into the alluvium-covered valley (Figure 1). On aerial photographs the fault trace is marked on the northeast side by denser vegetation that abruptly terminates at the trace (Figure 4). On the imagery this is clearly expressed by an alignment of very cool (dark) patches of alluvium along the northeast side of the trace (Figure 3). This is the best example in this area of imaging a fault that is not otherwise expressed by changes in topography or rock type. The temperature difference is probably related to the barrier effect of the fault on ground water movement. In the spring of 1961, which was a few months before the infrared survey, Farrell (1964, p. 34) measured a 50-foot difference in water table elevation across the fault in this vicinity. The shallower water table, hence higher moisture content, on the northeast side of the fault probably caused the cooler appearance on the imagery. Wallace and Moxham (1965, p. 24) reported similar radiometric expressions along the San Andreas fault in the Carrizo Plains, approximately 200 miles to the northwest.

INDIO HILLS FAULT

The Indio Hills fault forms the northeast border of the southeast end of the Indio Hills. Farther southeast it is marked by a ridge of Mecca Formation and then disappears. Toward the northwest the fault swings across the alluvium-covered valley and reappears in the Little San Bernardino Mountains.

TABLE 1. COMPARISON OF STRATIGRAPHIC-RADIOMETRIC UNITS

Unit	*Geologic Characteristics*	*Radiometric Characteristics*
Alluvium	Undeformed, unconsolidated sand and gravel covering valleys and dry stream channels	Relatively cool and uniform appearance. Some dry channels appear very cool
Poorly Stratified Bedrock	Deformed, moderately to poorly consolidated conglomerate, sandstone, and shale with poorly developed bedding	Relatively warm and uniform appearance. Some variations due to channels and scarps
Well Stratified Bedrock	Deformed, moderately to poorly consolidated, alternating, thick beds of sandstone and siltstone	Alternating bands of warmer and cooler imagery corresponding to sandstone and siltstone beds

Our imagery covers the southeast portion of the Indio Hills fault. The contact between cool alluvium and warm bedrock may be an expression of the barrier effect of the fault on ground water movement within the alluvium.

FOLDS

The numerous tightly folded anticlines and synclines in the bedrock trend generally N 70°W and are oblique to the major through-going faults (Dibblee, 1954, p. 26). The folds developed in response to the strike-slip movement along the faults; Edom Hill is a large anticline that was the site of an unsuccessful oil test.

Folds in the well-stratified bedrock are clearly shown on the infrared imagery by changes in strike of the alternating bands of warmer sandstone and cooler siltstone. This is particularly well illustrated at the southeast end of the hills (Figure 3 lower strip) and also occurs at the northwest end.

SUMMARY

Stratigraphic and structural information can be extracted from nighttime infrared imagery in the Indio Hills. Three stratigraphic-radiometric units are recognizable on the imagery and have the characteristics listed in Table 1.

Faults are expressed on the imagery in two ways: (1) as offsets of the stratigraphic-radiometric units; (2) as radiometric temperature anomalies related to blockage of ground water. The temperature anomalies consist of patches and streaks of cooler ground aligned parallel with the fault trace, and are recognizable only on the infrared imagery. This is a potentially useful technique that offers promise of locating faults that are covered by alluvium. The possibility of detecting areas of shallow ground water in arid land may also be important.

Folds are imaged as changes in the strike of the stratigraphic-radiometric units and are clearly expressed in the well stratified unit.

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