Geologic Interpretation from Composited Radar and Landsat Imagery

Composition and surface texture in Death Valley, California were discriminated by using like-polarized and cross-polarized synthetic-aperture radar composited with Landsat imagery.

INTRODUCTION

The purpose of this study was to obtain accurate discrimination of surficial geologic units in Death Valley, California by combining information on microwave scattering and reflectance data derived from a Landsat multispectral image. Previous work involving radar-Landsat combinations has concentrated on using imaging radar data to provide an apparent increase in resolution and to...
erties of the surface rather than by imaging geometry. In this exploratory study we have used processed synthetic-aperture radar (SAR) data acquired in like-polarized (vv) and cross-polarized (VH) modes and a total intensity Landsat image, which is "panchromatic" over the range from green (0.6 μm) to near infrared (1.1 μm).

**Landsat Data**

Multispectral Scanner (MSS) imagery from Landsat 2 was used in this study. MSS data are obtained in four bands: green (0.5 - 0.6 μm), red (0.6 - 0.7 μm), IR1 (0.7 - 0.8 μm), and IR2 (0.8 - 1.1 μm). The wide swath width (185 km) and moderate ground resolution (80 m) make Landsat imagery particularly useful for large-scale studies.

The brightness of the images generated by the MSS is a function of (1) surface spectral reflectance, (2) solar irradiance at the surface, (3) atmospheric transmission, (4) instrument response, and (5) scattering of sunlight by the atmosphere along the imaging line of sight. Generally, in a good and cloud-free Landsat frame, all the above parameters but the first one are nearly constant.

Reflectance of rocks and minerals in the visible and near infrared regions of the spectrum are controlled by electronic transitions in transition metal ions and, in the shorter visible and ultraviolet wavelengths, by electron transfer between ions. Iron in its two oxidation states is responsible for the color of most rocks and minerals in the field.

Rock type discrimination using spectral reflectance is difficult because the MSS sees only the weathered surfaces of rocks. The spectral reflectivity of weathered rocks is controlled by the abundance and oxidation state of iron. Coatings, such as desert varnish, can mask the original spectral signature of a rock. In addition, vegetation, which has a high reflectance in the near infrared, limits the usefulness of the two near infrared bands for geologic purposes in areas of vegetative cover (Rowan et al., 1974; Siegal and Goetz, 1977).

The Landsat frame used in this study was obtained on 20 April 1976. Figure 1 is a black-and-white intensity image of a portion...
of that frame showing Death Valley. Differences in reflectance are apparent in the surrounding mountains, the giant alluvial fans on the west side of the valley, and the salt pan at the bottom of the valley. Linear features are also clearly discernible.

Reflectance variations on the alluvial fans in Death Valley correlate with differences in amount of desert varnish. Desert varnish is a dark brown to black coating that forms on exposed surfaces of rocks of all lithologies in moist desert regions. Recent work by Potter and Rossman (1977 a,b) indicates that the coating is composed of 70 to 90 percent clay minerals with a small amount of manganese and iron oxides which supply the color. Material for the varnish appears to be derived from outside sources, such as windblown sediment, and not the rock substrate (Potter and Rossman, 1977 a,b).

Three alluvial fan gravel units (Qg2, Qg3, and Qg4) were mapped by Hunt and Mabey (1966). Qg2 is the oldest and forms elevated remnants which preserve the original fan form. The surface of the number 2 gravel is a smooth desert pavement of interlocking fragments of disintegrated pebbles and cobbles. The desert pavement is a very stable surface which has enabled a dark coating of desert varnish to develop.

Desert varnish is also well-developed on the gravel of intermediate age, Qg3. These gravels stand slightly above present washes and are less weathered than Qg2. The fact that both Qg2 and Qg3 have a coating of desert varnish, even though they differ in age, makes them hard to separate in Landsat imagery. Variations in reflectance exist, but these do not correlate with the units of Qg2 and Qg3. A correlation does exist, however, between the lightest areas on the fans and the youngest gravel unit, Qg4. This unit occupies the presently active channels on the fans and, because of frequent abrasion, has very little desert varnish.

The evaporite units on the floor of Death Valley have inconsistent and ambiguous signatures at visible and near-infrared wavelengths. The rough facies of the silty rock salt unit, Qhr, while not shown separately on the geologic map of Figure 2, appear as bright spots approximately 1 km east of the base of Trail Canyon fan. They also appear as a dark patch about 10 km south of Furnace Creek Ranch. Adjacent to this patch on its northeast side is a lighter patch which is a continuation of Qhr, Qhe (eroded salt unit), and some Qhs (smooth facies, silty rock salt unit). This area has a grey tone very similar to that of the massive rock salt unit (Qh) of Badwater Basin. This could be due to a combination of factors, including silt mixed with Qhr and Qhs and shadowing effects in the rougher Qhe and Qh. Lighter tones characterize many evaporite units. Flood plain deposits (Qf) with their thin, clean salt crusts, and most exposures of Qhe and Qhs in the Cottonball Basin all appear in light tones.

Radar Observations

Geologic applications of imaging radars have included comparative studies of alluvial fans (Daily, 1975) and studies of alluvial and evaporite units in Death Valley (Schaber et al., 1976).

For the three important alluvial units in Death Valley, Schaber et al. (1976) found that desert pavement (Qg2 on Figure 2) was readily distinguished from the younger of the upper Pleistocene fan gravels (Qg3 and the recent fan gravels (Qg4) on the basis of L-band radar backscatter. The very low radar return from the desert pavement is a consequence of the smoothness of the surface, whereas the two fan gravel units (Qg3 and Qg4) are indistinguishable because they have similar roughnesses. Using multifrequency, multipolarization radar data, Daily et al. (1978 a) also found that the pavement was distinguishable from the other fan gravels, but that the two gravel units could not be discriminated.

Multipolarization (L(VV) and L(VH)) radar data proved to be very useful in discriminating among the evaporite units of the valley floor. The extremely rough massive salt unit (Qh) gives strong depolarized returns due to multiple scattering effects (Daily et al., 1978 b). The less rough eroded salt units still had significant backscatter but had no associated polarization anomalies. Of the evaporite units, only the floodplain (Qf) defied classification. As shown by Daily et al., (1978 a), the floodplain was characterized by substantial variations in backscatter that were attributable to penetration to and reflection from a brine aquifer that underlies the floodplain at variable depth.

Landsat—Multipolarization Radar Image

By combining the Landsat intensity images in like (vv) and cross (vh) polarization, we sought to display on one composite color image most of the information in the three input images. The registration was done digitally after the selection of a number of clearly recognizable tie points.
As mentioned in the section on Landsat Data, the Landsat image contains information on the reflectance of the surface rocks and minerals. This reflectance is controlled by electronic transitions (i.e., nature of the rock) in the top few micrometres. On the other hand, the radar images contain information on the surface roughness, particle size, and dielectric constant of the top few centimetres (Note: dielectric constant is highly dependent on moisture content). The like-polarized image brightness is directly proportional to the surface roughness at the scale which satisfies the Bragg conditions, i.e., $\lambda = \lambda/2 \sin \theta$ where $\theta$ is the incidence angle and $\lambda$ is the radar wavelength. The cross-polarized image brightness is proportional to the overall roughness spectrum of the surface (Valenzuela, 1968; Daily et al., 1978 a). In the case of surfaces covered by discrete scatterers, such as boulders on the alluvial fans, the like-polarized brightness is mainly related to the size of the scatterers relative to the wavelength, while the cross-polarized brightness is mostly affected by multiple scattering which, in turn, is related
to the density of scatterers per unit area. Therefore, the information in the radar images and the Landsat images is complementary, especially in the case of Death Valley where the physical properties of the surface (e.g., roughness) are strongly related to the surface lithology.

In the Landsat-radar false-color composite in Plate 1, details on the alluvial fans are more easily seen. Differences in some of the evaporite units on the salt pan are apparent. Stronger topographic effects are evident, though topography is still a problem and causes some local registration errors. Some effects of dual-polarization radar can be seen in the composite, especially in the salt pan. The MSS can differentiate between alluvial fan surfaces with different desert varnish; however, it is insensitive to roughness differences that distinguish active surfaces from desert pavements. The L-band radar can easily discern desert pavements, but is blind to variations in desert varnish. Therefore, a Landsat-radar composite allows the mapping of the gravel units, defined by Hunt and Mabey (1966), which are characterized by the amount of desert varnish, gravel size, and topographic context.

Trail Canyon fan is shown in detail in Plate 2a. Desert pavement areas are obvious as dark red elongated bodies extending radially from the apex of the fan. These areas are shown on the enlargement of the geologic map of Hunt and Mabey (1966) (Plate 2b) as $Q_g$, the oldest gravel unit on the alluvial fans. They are dark red in the composite because of the large amount of desert varnish and the very smooth desert pavement on these old surfaces. Some return, though, is apparent from the Landsat image.

The next oldest gravel unit is $Q_g$ and is depicted on the composite as a light blue-green. This unit is dark with desert varnish but is rough to the L-band radar and therefore bright.

The youngest gravel unit, $Q_h$, is light red or magenta in color indicating it is bright in all components. Because $Q_g$ and $Q_h$ appear the same in L-band imagery, the spatial resolution of Landsat limits the resolution between $Q_g$ and $Q_h$.

Along the base of the fans is a band that appears very dark red. This indicates a return from Landsat, but no return from L-band $\nu \nu$ or $\nu v$ polarizations. The L-band $\nu \nu$ polarization radar imagery of the area at the base of the fans has been studied by Schaber et al. (1976), who found a systematic decrease in grain size toward the foot of the fans. This grain size decrease passed through the Rayleigh criterion for specular reflection for L-band wavelengths at a fairly well-determined point in grain size, producing a dark band in imagery at the foot of the fans. The higher albedo in Landsat imagery is the result of disintegration of rocks, leading to little desert varnish at the foot of the fans.

Flood deposits in the southern part of Badwater Basin exhibit polarization effects. The color composite shows this area as red and yellow. The like polarized L-band imagery ($\nu v$) is bright, probably because of penetration effects. Landsat is bright because of the salt crust that covers most of the flood deposits on the salt pan of Death Valley. The purer salts in the flood deposits are lighter than the salts of the massive rock salt unit ($Q_h$). This albedo effect combined with roughness variations allows many details in the salt pan to be seen. In extremely rough terrains, passive reflection data (i.e., visible and near infrared) will be strongly modified by shadowing effects. Except for the special case of imaging at local noon at the solar equator, two effects exist: (1) Overall decrease in albedo because of shadowing effects, and (2) Spectral shifts generated by the contribution of those areas in shadow that are illuminated by sources having spectral properties different from direct sunlight (sky, multiple reflections from surface). Evaluation of this effect would involve:

- Multiple imaging at different times of day. This option is not possible for rotation-synchronous platforms (e.g., Landsat).
- Imaging by a sensor that is sensitive to roughness. Knowledge of both the local sun angle and roughness properties of the surface will permit a semiquantitative albedo correction to be made.
- Use of atmospheric scattering model to correct for differential effects as a function of $\nu x$.

As an example, the surface of the Devil's Golf Course ($Q_h$) consists of steep-sided towers and cavities having local slopes ranging from 45 to 90 degrees. The Landsat image, acquired at a sun angle of 48 degrees shows $Q_h$ as a distinctly darker unit than adjacent $Q_f$ (flood-plain deposits). Field measurement of shadows for a sun angle of 50 degrees show:

- Shadow brightness (estimated from a camera light meter) is less than 10 percent of the reflectivity of a fully illuminated portion of the silty salt.
- Approximately 20 percent of the surface as seen from above is in shadow.

Taking the albedo of the shadows to be zero, the calculated effect of shadowing is a reduction of the albedo of $Q_h$ by 20 percent.

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Taking a nominal albedo of 0.5 for silty salt (Neal, 1965) shadowing at 10:00 a.m. reduces Qh's albedo to 0.40. A similar situation occurs on the rough active fans.

In the above situation, the optical sensors can confuse roughness effects with lithology. Information on surface texture derived from multipolarization, multifrequency radar images permit a semiquantitative albedo correction to be made.

In the case of the Devil's Golf Course, such a correction would decrease the contrast between the massive salt and other nearby salt units. For the alluvial fan units, however, the correction would tend to separate the two older units, \( Q_{g1} \) and \( Q_{g2} \). The younger Pleistocene fan gravel unit \( Q_{g2} \) is less weathered and, therefore, more reflective at visible wavelengths than is desert pavement \( Q_{g1} \), but the gravels are rough and thus shadowed. Similar roughness-related albedo effects exist on recent volcanic outcrops (Lefebvre and Abrams, 1977).

The foregoing analysis fails for the floodplain unit \( Q_f \) for which radar backscatter is not always a function of surface roughness. Because penetration is proportional to wavelength, short-wavelength radars (X- or K-band) are more likely to succeed in correctly classifying the floodplain.

**Conclusion**

In Death Valley, Quaternary surficial geologic units are defined on the basis of both composition and surface roughness. Any attempt to classify the units by remote sensing should use sensors sensitive to composition (Landsat imagery) and to centimetre-scale surface texture (multipolarization radar imagery). We have generated a color composite whose primary colors correspond to the three input images, Landsat, vv, and vh, by geometrically matching L-band radar imagery to Landsat format. The composite image (1) achieves a nearly complete discrimination of the surficial geologic units of Hunt and Mabey (1966), and (2) provides, in synoptic form, information on two important surface properties, composition and surface texture.

Surface roughness parameter deduced from radar backscatter and depolarization properties may be useful in making first-order albedo corrections to Landsat imagery. Second-order corrections to spectral signatures will require modeling of the effects of the secondary illumination sources (sky, multiple scattering). Some of the difficulties encountered by Rowan et al. (1974) in discriminating playas and hydrothermally altered zones on certain types of processed Landsat imagery may be correctable by radar techniques.

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**References**


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