Remote sensing for petroleum exploration, Part 1: Overview of imaging systems

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This paper, the first of two that summarize remote sensing as applied to petroleum exploration, provides an overview of the science and the computer techniques used to process the data. The second (to be published in *TLE*'s May issue) will describe successful oil-exploration projects that employed remote-sensing technology. The examples are from projects by colleagues and myself at Chevron, from which I retired in 1992.

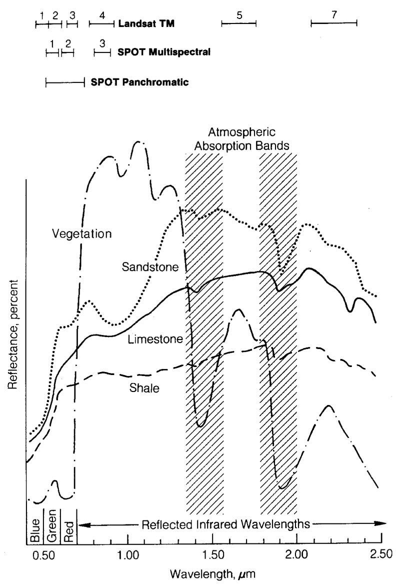

Figure 1. Reflectance spectra of vegetation and sedimentary rocks, showing spectral ranges of Landsat TM and SPOT systems. All figures in Part 1 are from Sabins (1997).

Remote sensing has several applications to geophysical exploration of onshore regions. Images are interpreted to produce geologic maps that show structural trends and potential prospects which are, in turn, used to plan an efficient seismic program. Furthermore, if an area lacks a reliable base map, one can be readily generated from remote-sensing data, as can maps showing access and trafficability which can also improve the efficiency of field operations. (When Lee Lawyer, a former SEG President, was chief geophysicist of Chevron Overseas Petroleum, he insisted that any onshore seismic survey be preceded by a remote-sensing interpretation.) Landsat images have also been employed in shallow offshore areas to identify uncharted reefs and other hazards to seismic surveys.

Remote sensing is defined as *the science of acquiring, processing, and interpreting images from satellites and aircraft that record the interaction between matter and electromagnetic energy*. Remote-sensing images of the earth are acquired in three wavelength intervals, or regions, of the electromagnetic spectrum. The visible region ranges from 0.4 to 0.7 µm and is divided into the blue, green, and red bands. The infrared (IR) region ranges from 0.7 to 30 µm and is divided into the reflected IR and thermal IR portions. The reflected IR portion ranges from 0.7 to 3.0 µm; the energy is predominantly reflected sunlight at wavelengths longer than visible light. The Landsat and SPOT satellite systems acquire valuable images in the visible and reflected IR regions. The thermal IR portion ranges from 3.0 to 15.0 µm; the energy is radiant, or heat, energy. Thermal IR images have considerable potential for exploration in arid and semiarid terrains; however, the method has been underutilized in recent years largely owing to the lack of suitable images.

Images in the visible, reflected IR and thermal IR are acquired in the passive mode by systems that simply record the available energy that is reflected or radiated from the earth. The microwave region ranges from 0.1 to 30 cm; images for exploration are primarily acquired in the active mode called radar. This paper focuses on three systems: Landsat Thematic Mapper and SPOT panchromatic images in the visible and reflected IR regions, and aircraft radar images.

Landsat Thematic Mapper images. Landsat is an unmanned satellite that orbits the earth in a sun-synchronous pattern at an altitude of 705 km. The two second-generation satellites carry the thematic mapper (TM) system. TM is a multispectral system which records seven separate

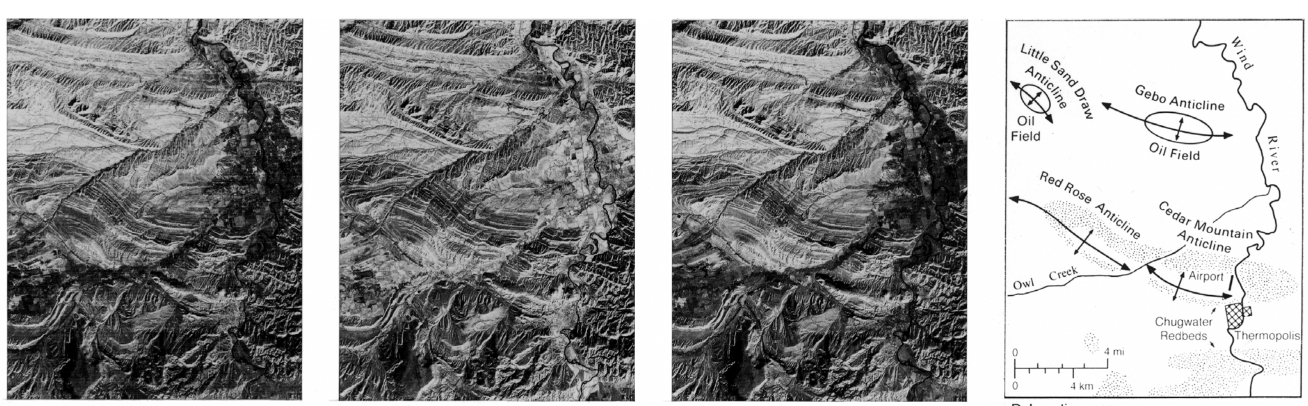

Figure 2. Landsat TM bands. (a) = 2 (green), (b) = 4, and (c) = 7 (both reflected IR). (d) = geologic features near Thermopolis, Wyoming, as interpreted from Figure 3.

images, or bands, for each scene. Figure 1 shows wavelength ranges of the three visible bands (1, 2, 3) and three reflected IR bands (4, 5, 7). Band 6 records thermal IR energy but is rarely used for exploration. The reflectance spectra of common sedimentary rocks and vegetation in Figure 1 provide insights for selecting the optimum TM bands for interpretation. The spectra of the different rocks are very similar in the visible bands but have major distinctions in the reflected IR bands; therefore, TM bands 4, 5, and 7 are especially useful for mapping different rock types.

TM images are acquired by a cross-track scanner with an oscillating mirror that sweeps across the terrain normal to the satellite ground track. A spectrometer separates the reflected sunlight into the six spectral bands. The image data are telemetered to ground receiving stations via the tracking and data relay satellites (TDRSS). A TM image covers 170 × 185 km^2 of terrain with a spatial resolution of 30 m. The digital data are stored in a raster format. An individual band consists of 5667 scan lines, each of which contains 6167 picture elements (pixels) for a total of almost 35 million pixels. A pixel represents a 30 × 30 m ground-resolution cell and records the intensity of reflected energy on an eight-bit scale, ranging from 0 (minimum reflectance) to 255 (maximum reflectance).

Any three bands may be merged in any combination of blue, green, and red to produce a color composite image. There are 120 possible color combinations, but theory and experience show that a small number of combinations are suitable for most regions and applications. Figure 2 shows TM bands 2, 4, 7 for a small subarea that includes the town of Thermopolis in the Bighorn Basin of Wyoming. These bands are generally optimum for arid and semiarid terrain, such as central Wyoming. Figure 3 is a color composite of bands 2, 4, 7 merged in blue, green, and red. Figure 2d is a map showing major geologic features interpreted from this small-scale color image. Four anticlines are seen in the image. The Little Sand Draw and Gebo anticlines are oil fields that were discovered long before the launch of Landsat. Images of existing oil fields are valuable examples for interpreting images of frontier regions. Detailed maps at scales as large as 1:50 000 are

Figure 3. Color composite image of TM bands 2, 4, and 7 combined in blue, green, and red. Thermopolis, Wyoming subarea.

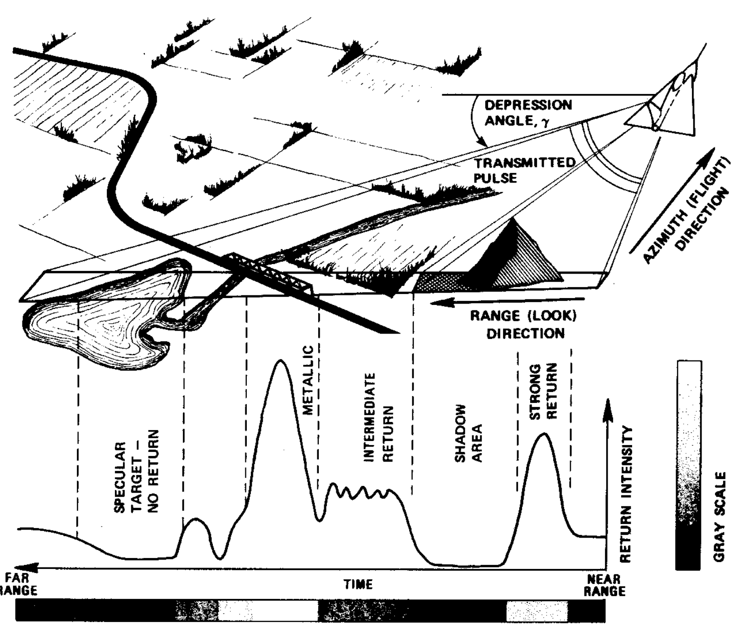

Figure 4. Terrain returns and image signatures for a pulse of radar energy.

interpreted from larger-scale versions of TM images. Part 2 of this article will describe how TM images contributed to oil discoveries in the Central Arabian Arch.

Landsat was launched by NASA and is operated by Space Imaging EOSAT. Images, in digital or hardcopy format, are sold by Space Imaging EOSAT, 4300 Forbes Boulevard, Lanham, Maryland 20706 (http://origin.eosat.com/) and by the USGS EROS Data Center, Sioux Falls, South Dakota 57198 (http://edcwww.er.usgs.gov/).

SPOT images. The SPOT unmanned satellite orbits the earth in a sun-synchronous pattern at an altitude of 832 km. Images are acquired by along-track scanners in which linear arrays of detectors are aligned normal to the ground track. As the satellite moves forward, each detector sweeps a narrow strip of terrain parallel with the track. SPOT images cover 60 × 60 km^2 of terrain and are acquired in two modes: SPOT panchromatic (pan) and SPOT multispectral (XS). Figure 1 shows the spectral ranges of these images. The SPOT pan system records a single image in the spectral band 0.51 to 0.73 μm with a spatial resolution of 10 m. The SPOT XS system records three images in the green, red, and reflected IR bands, with a spatial resolution of 20 m. The XS system does not acquire images in the wavelength intervals of TM bands 5 and 7. The SPOT scanner may be tilted to acquire images up to 475 km to the east or west of the ground track, which provides two advantages:

- An area may be imaged up to 11 times during the 26-day repeat cycle, depending upon its latitude.
- Two images of an area acquired from different orbit paths have parallax which enables them to be viewed stereoscopically. SPOT stereo images have been used to prepare detailed contour maps of exploration concessions that lack conventional topographic maps.

The regional coverage and spatial resolution of TM images are well suited for regional mapping. The higher spatial resolution and stereo capability of SPOT pan images are well suited for detailed local mapping. SPOT images and data are sold by SPOT Image Corporation, 1897 Preston White Drive, Reston, Virginia 22091-4368 (http://www.spot.com/).

Radar images. Radar is an active form of remote sensing that is shown diagrammatically in Figure 4. Pulses of microwave energy, at wavelengths of a few centimeters to a few tens of centimeters, are directed to the terrain from an antenna carried on an aircraft or satellite. Energy is directed downward toward the side of the ground track. The angle between the horizon and the radar beam is called the depression angle. Each radar pulse "illuminates" a narrow strip, or scan line, of terrain normal to the track. Figure 4 shows a single scan line. Figure 5b is a typical radar image which consists of many scan lines. The incident energy interacts with the terrain, and portions are returned to the radar system which records the data. Three characteristics of terrain determine the intensity of the radar return:

- Dielectric constant, which is largely a function of moisture content.
- Surface roughness at a scale of centimeters. Smooth surfaces, such as calm water, have dark signatures. Rough surfaces, such as forests and coarse gravel, have bright signatures.
- Topography. Figure 4 shows that slopes facing toward the radar antenna have bright signatures, called highlights. Slopes facing away from the antenna have dark signatures, called shadows. This attribute of radar is most important for geologic interpretation.

Figure 4 shows the analog signal that is received for the scan line. The signal is digitized and recorded for later processing and playback to produce images. Modern radar images are acquired in the synthetic aperture (SAR) mode that achieves high spatial resolution, even at satellite altitudes. Topographic maps are produced from repeated images using the process called interferometer SAR (IFSAR).

Radar images have two major advantages over visible and reflected IR images, such as Landsat and SPOT. Because radar is an active system that provides its own source of energy, images can be acquired day or night and through dense clouds or fog. Aircraft radar images are typically acquired with a low depression angle of 20° or less (Figure 4) which causes strong highlights and shadows from topographic features that may express geologic structures.

Figure 5 compares an aircraft radar image with a Landsat TM image of the Mapia anticline in Irian Jaya, Indonesia. The TM image was acquired with a sun elevation of 45° above the horizon and lacks strong highlights and shadows. The aircraft radar image was acquired with a depression angle of 17°. The resulting highlights and shadows enhance the dip slopes in the upper portion of the radar image and the flanks of the anticline in the lower portion. Figure 6 is a geologic interpretation of the image. In addition to structure, different rock types are also recognized by their distinctive signatures. Fan deposits along the upper margin of the image (Figure 5b) form broad slopes with no stratification. The upper member of the Buru Formation (Tbu in Figure 6) has a distinctive ledge-and-slope topography

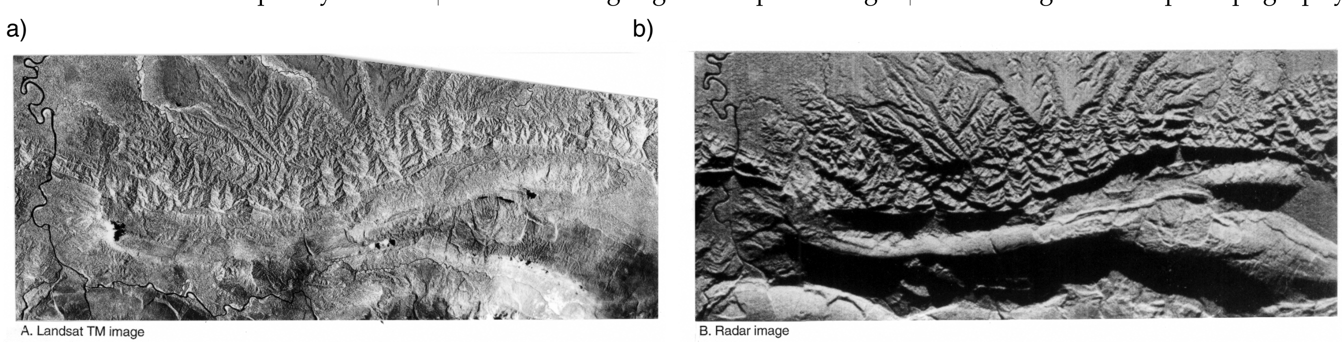

Figure 5. Comparison of (a) Landsat and (b) aircraft radar images over Mapia anticline, Irian Jaya, Indonesia.

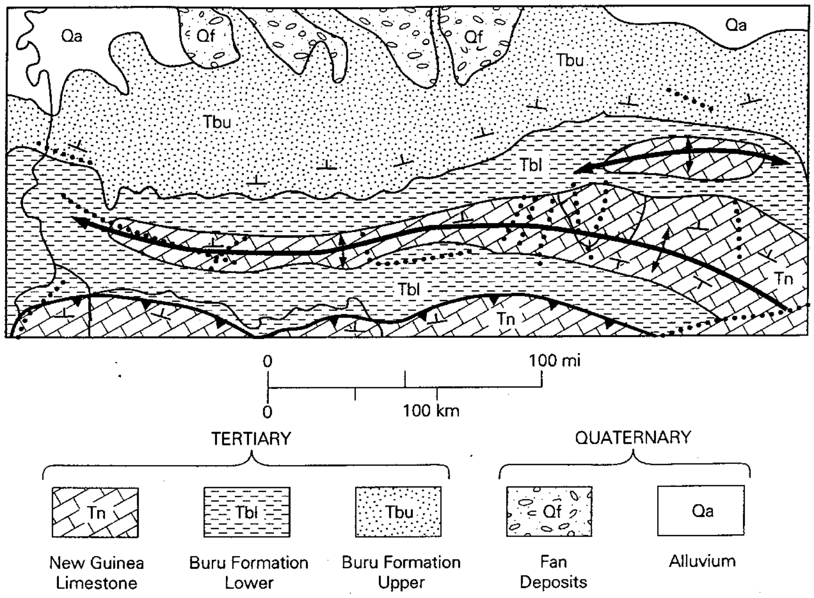

Figure 6. Geologic interpretation of radar image of Mapia anticline, Irian Jaya.

caused by the interbedded resistant sandstone and nonresistant shale. The nonresistant shale of the lower member of the Buru Formation (Tbl) forms a broad valley. The New Guinea Limestone (Tn) forms the broad arch of the Mapia anticline. The uneroded nature of the limestone indicates that it has been exposed relatively recently. In humid regions, prolonged erosion of limestones produces karst topography with a distinctive pitted signature. The radar image is clearly preferable to the TM image for geologic interpretation. This enhancement of geologic features misled some early interpreters to believe that radar energy penetrated a forest canopy and imaged the underlying surface. Both radar theory and images show that radar signatures are largely the result of interactions with the upper few centimeters of vegetation. Part 2 will describe how radar images contributed to oil discoveries in the rain forest terrain of Papua New Guinea.

NASA has conducted three radar missions of earth from the Space Shuttle, called Shuttle Imaging Radar (SIR). Images of the eastern Sahara in Egypt and Sudan showed that the radar energy penetrated up to several meters of sand and imaged the underlying bedrock. Field and laboratory investigations showed that this penetration occurred because of the hyperarid environment. Only a few additional examples of sand penetration have been documented. Other desert sands apparently contain sufficient moisture to attenuate the radar energy. Information on the SIR-C images acquired in 1994 is available on the EROS Data Center Web site (http://edcwww.cr.usgs.gov/landacc/sir-c/sir-c.html).

Several unmanned satellites are acquiring radar images. The Japan Earth Resources (JERS) and the European Remote Sensing (ERS) satellites acquire images at a steep depression angle that results in geometric distortion called layover. These images are not suitable for geologic interpretations of terrain with moderate or high relief. The Canadian Radarsat satellite acquires images at a variety of depression angles and formats, several of which are suitable for geologic interpretation. Images and information are available from Radarsat International 3851 Shell Road, Richmond, British Columbia V6X 2W2 (http://www.rsi.ca).

Digital image processing. Except for conventional aerial photographs, all remote-sensing images are acquired in digital format and are computer processed to produce images for interpretation. This paper will simply describe the three functional categories of image processing and list representative processing routines.

- *Image restoration* compensates for data errors, noise, and geometric distortions introduced during the scanning, recording, and playback operations. This includes restoring line dropouts; restoring periodic line striping; restoring line offsets; filtering random noise; correcting for atmospheric scattering; and correcting geometric distortions.
- *Image enhancement* alters the visual impact that the image has on the interpreter in a fashion that improves the information content. This includes contrast enhancement; density slicing; edge enhancement; making digital mosaics; intensity, hue, and saturation transformations; merging data sets; and synthetic stereo images.
- *Information extraction* utilizes the decision-making capability of the computer to recognize and classify pixels on the basis of their digital signatures. The major results are principal-component images; ratio images; multispectral classification; and change-detection images.

These routines are described and illustrated in the book by Sabins (see "Suggestions for further reading").

Summary. Landsat TM, SPOT, and radar images are covered in this review because the images are readily available and are well suited for oil exploration. The data are primarily available in digital format and require specialized computer processing and reproduction to produce images suitable for interpretation. Unless a user is familiar with image processing, it is advisable to employ a contract organization to provide these services.

Suggestions for further reading. A basic reference is *Remote Sensing — Principles and Interpretation*, Third Edition, by Sabins (W. H. Freeman, 1997). The American Society for Photogrammetry and Remote Sensing publishes the *Manual of Remote Sensing*. The third edition is in press and should be available soon. The Internet is an excellent source of images and information. The Web's Virtual Library: Remote Sensing site (http://www.vtt.fi/aut/ava/rs/virtual/) provides extensive links to information sources. LE

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