Chapter 22B. Analysis of Imaging Spectrometer Data for the Kunduz Area of Interest

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Abstract
Imaging spectrometer data collected over the southern part of the Kunduz area of interest (AOI) in northeastern Afghanistan were analyzed with spectroscopic methods to identify the occurrence of selected materials at the surface. Absorption features in the spectra of HyMap data were compared to a reference library of spectra of known materials. Green and dry vegetation cover most of the surface of the Kunduz AOI. In the areas with exposed rocks and soils, carbonate minerals are the most abundant. Associations of hematite with clays are consistent with the red clays in the early Miocene sedimentary rocks in the area. The known Kunduz celestite deposit was not covered by the airborne survey.

22B.1 Introduction
Past studies of geologic data of Afghanistan revealed numerous areas with indications of potential mineral resources of various types (Peters and others, 2007; Abdullah and others, 1977). Several of these areas were selected for follow-on studies using imaging spectroscopy to characterize surface materials. Imaging spectroscopy is an advanced type of remote sensing, which is also known as hyperspectral remote sensing. One of the selected areas is the Kunduz area of interest (AOI) in northeastern Afghanistan, which is approximately 200 km north of Kabul (fig. 22B–1). The area may have potential for the presence of celestite minerals. To help assess these potential resources, high-resolution imaging spectrometer data were analyzed to detect the presence of selected minerals that may be indicative of past mineralization processes and the accumulation of potential economic mineral concentrations. This report contains the results of the spectroscopic data analyses.

22B.2 Data Collection and Processing
In 2007, imaging spectrometer data were acquired over most of Afghanistan as part of the U.S. Geological Survey (USGS) project "Oil and Gas Resources Assessment of the Katawaz and Helmand Basins.” These data were collected to characterize surface materials in support of assessments of resources (coal, water, minerals, and oil and gas) and earthquake hazards in Afghanistan (King and others, 2010). Imaging spectrometers measure the reflectance of visible and near-infrared light from the Earth’s surface in many narrow channels, producing a reflectance spectrum for each image pixel. These reflectance spectra can be interpreted to identify absorption features that arise from specific chemical transitions and molecular bonds that provide compositional information about surface materials. Imaging spectrometer data can only be used to characterize the upper surface materials and not subsurface composition or structure. However, subsurface processes can be indicated by the distribution of surface materials that can be detected using imaging spectroscopy data.

22B.2.1 Collection of Imaging Spectrometer Data
The HyMap imaging spectrometer (Cocks and others, 1998) was flown over Afghanistan from August 22 to October 2, 2007 (Kokaly and others, 2008). HyMap has 512 cross-track pixels and covers the wavelength range 0.43 to 2.48 microns (µm) in 128 channels. The imaging spectrometer was flown on a WB-57 high-altitude aircraft at 50,000 ft. There were 207 standard data flight lines and 11 cross-
cutting calibration lines collected over Afghanistan for a total of 218 flight lines, covering a surface area of 438,012 km² (Kokaly and others, 2008). Data were received in scaled radiance form (calibrated to National Institute of Standards and Technology reference materials). Before processing, four channels that had low signal-to-noise ratios and (or) were in wavelength regions overlapped by adjacent detectors were removed from the HyMap data. Each flight line was georeferenced to Landsat base imagery in UTM projection (Davis, 2007).

![Index map of the Kunduz area of interest, northeast Afghanistan.](image)

**Figure 22B–1.** Index map of the Kunduz area of interest, northeast Afghanistan.

**22B.2.2 Calibration**

HyMap data were converted from radiance to reflectance using a multi-step calibration process. This process removed the influence of the solar irradiance function, atmospheric absorptions, and residual instrument artifacts, resulting in reflectance spectra that have spectral features that arise from the material composition of the surface. Because of the extreme topographic relief and restricted access to ground-calibration sites, modifications to the standard USGS calibration procedures were required to calibrate the 2007 Afghanistan HyMap dataset (Hoefen and others, 2010). In the first step of the calibration process, the radiance data were converted to apparent surface reflectance using the radiative transfer correction program Atmospheric CORrection Now (ACORN; ImSpec LLC, Palmdale, Calif.). ACORN was run multiple times for each flight line, using average elevations in 100-m increments, covering the range of minimum to maximum elevation within the flight line. A single atmospherically
corrected image was assembled from these elevation-incremented ACORN results. This was done by determining the elevation of each HyMap pixel and selecting the atmospherically corrected pixel from the 100-m increment closest to that elevation.

Each assembled atmospherically corrected image was further empirically adjusted using ground-based reflectance measurements from a ground-calibration site. Five ground-calibration spectra were collected in Afghanistan: Kandahar Air Field, Bagram Air Base, and Mazar-e-Sharif Airport, as well as, soil samples from two fallow fields in Kabul. At each site, the average field spectrum of the ground target was used to calculate an empirical correction factor using the pixels of atmospherically corrected HyMap data in the flight lines that passed over the site. Subsequently, each of the HyMap flight lines was ground-calibrated using the empirical correction from the closest calibration site.

To further improve the data quality, an additional calibration step was taken to address the atmospheric differences caused, in part, by the large distances between the calibration sites and the survey areas. The large distances were a result of the lack of safe access to ground-calibration sites. The duration of the airborne survey and variation in time of day during which flight lines were acquired also resulted in differences in atmospheric conditions between standard flight lines and lines over ground-calibration sites, which were used to derive the empirical correction factors. Over the course of the data collection, the sun angle, atmospheric water vapor, and atmospheric scattering differed for each flight line. To compensate for this, cross-cutting calibration flight lines over the ground-calibration areas were acquired (Kokaly and others, 2008) and used to refine the reflectance calculation for standard data lines. A multiplier correction for standard data lines, typically oriented as north-south flight lines, was derived using the pixels of overlap with the well-calibrated cross-cutting lines, subject to slope, vegetation cover, and other restrictions on pixel selection (Hoefen and others, 2010). As a result, the localized cross-calibration multiplier, derived from the overlap region, reduced residual atmospheric contamination in the imaging spectrometer data that may have been present after the ground-calibration step.

After undergoing the above calibration process, the georeferenced and calibrated reflectance data were processed. The reflectance spectrum of each pixel of HyMap data was compared to the spectral features of reference entries in a spectral library of minerals, vegetation, water, and other materials (King and others, 2011; Kokaly and others, 2011). The best spectral matches were determined for each pixel, and the results were clustered into classes of materials discussed below.

HyMap reflectance data were processed using MICA (Material Identification and Characterization Algorithm), an Interactive Data Language (IDL) module of the U.S. Geological Survey PRISM (Processing Routines in IDL for Spectroscopic Measurements) software (Kokaly, 2011). The MICA analysis compared the reflectance spectrum of each pixel of HyMap data to entries in a reference spectral library of minerals, vegetation, water, and other materials. The HyMap data were compared to 97 reference spectra of well-characterized mineral and material standards. The resulting maps of material distribution, resampled to 23 × 23 meter square pixel grid, were mosaicked to create thematic maps of surface mineral occurrences over the full dataset covering Afghanistan.

MICA was applied to HyMap data twice to present the distribution of two categories of minerals that are naturally separated in the wavelength regions of their primary absorption features. MICA was applied using the subset of minerals with absorption features in the visible and near-infrared wavelength region, producing a 1-µm map of iron-bearing minerals and other materials (King and others, 2011), and again using the subset of minerals with absorption features in the shortwave infrared, producing a 2-µm map of carbonates, phyllosilicates, sulfates, altered minerals, and other materials (Kokaly and others, 2011). For clarity of presentation, some individual classes in these two maps were bundled by combining selected mineral types (for example, all montmorillonites or all kaolinites) and representing them with the same color in order to reduce the number of mineral classes. The iron-bearing minerals map has 28 classes. Iron-bearing minerals with different mineral compositions but similar broad spectral features are difficult to classify as specific mineral species. Thus, generic spectral classes, including several minerals with similar absorption features, such as Fe$^{3+}$ Type 1 and Fe$^{3+}$ Type 2, are depicted on
the map. The carbonates, phyllosilicates, sulfates, and altered minerals map has 32 classes. Minerals with slightly different compositions but similar spectral features are less easily discriminated, thus, some identified classes consist of several minerals with similar spectra, such as the chlorite or epidote class. When comparisons with reference spectra provided no viable match, a designation of “not classified” was assigned to a pixel.

22B.3 Geologic Setting of the Kunduz Area of Interest

The Kunduz AOI is mainly within the Kunduz Province in northeastern Afghanistan, but the southern part is in the Baghlan Province. The contrast-enhanced natural-color composite of Landsat Thematic Mapper bands in figure 22B–2 provides a general overview of the Kunduz AOI terrain and is useful for understanding the general characteristics and distribution of surficial material including rocks and soil, unconsolidated sediments, vegetation, and hydrologic features.

![Contrast-enhanced Landsat Thematic Mapper natural-color image of the Kunduz area of interest. Geologic contacts and faults from Doebrich and others (2006).](image)

**Figure 22B–2.** Contrast-enhanced Landsat Thematic Mapper natural-color image of the Kunduz area of interest. Geologic contacts and faults from Doebrich and others (2006).

22B.3.1 Topography

Elevations in the Kunduz AOI range between 329 and 1,683 m (fig. 22B–3). The highest areas are in the southern part of the Kunduz AOI in well-defined ranges and foothills. The low areas include large agricultural areas in the south and along the eastern edge of the AOI.
22B.3.2 Lithology and Structure

The oldest rocks in the AOI are Early Cretaceous red sandstones, siltstones, conglomerates, gypsiums, and clays exposed in the south-central portion of the area (fig. 22B–4; Doebrich and others, 2006; Abdullah and Chmyriov, 1977). Eocene and Miocene sedimentary rocks also crop out in the area, including a conspicuous unit of Early Miocene red clay. The lower elevations, which make up the majority of the Kunduz AOI, are covered by Quaternary and Recent surficial deposits.

22B.3.3 Known Mineralization

Figure 22B–5 shows one location where a potential for celestite mineral resource development may exist (Peters and others, 2007). Celestite in the Kunduz deposit occurs in the Paleogene Suzuksk and Buhkharsk Formations, which are overlain by unconsolidated Quaternary sediments (Abdullah and others, 1977). Celestite-bearing beds as much as 1,400 m long and 0.9 to 1.5 m thick have been reported (Abdullah and others, 1977). Unfortunately, the imaging spectrometer data do not extend as far north as this deposit.
**22B.4 Mineral Maps of the Kunduz Area of Interest**

Only the southern two-thirds of the Kunduz AOI was covered by the HyMap airborne imaging spectrometer survey. Spectroscopic analysis of these HyMap imaging spectrometer data resulted in the identification of a variety of minerals exposed at the surface. Although the occurrence of certain minerals may suggest that mineralization processes may have once operated in the area, many of the minerals that were identified are also common rock-forming minerals or minerals that can be derived from the weathering of a wide variety of rock types. Consequently, the distribution patterns of the identified minerals and the geologic context in which they occur are extremely important in understanding the causes of mapped mineral occurrences and evaluating the possible potential for related mineral deposits.

Figures 22B–6 depicts the results of the Material Identification and Characterization Algorithm (MICA) analyses of the HyMap data for the Kunduz AOI for the 2-µm materials (clays, carbonates, phyllosilicates, sulfates, altered minerals, and other materials). Figure 22B–7 shows the results for the iron-bearing (1 µm) minerals. Green and dry vegetation dominate the spectral character of the data for most of the area. The carbonates are the most dominant minerals detected in the Kunduz AOI, indicated by pixels containing the calcite and calcite mixed with clay/mica classes. Gypsum was not detected in the area.
Figure 22B–5. Sites of mineralization (Peters and others, 2007) indicated by deposit type on the geologic map of the Kunduz area of interest from Doebrich and others (2006) and Abdullah and Chmyriov (1977).

Because of the large number of classes represented and the subtleties of the distribution patterns represented in mineral maps, it is instructive to display these results as a series of image maps each depicting a selected group of minerals that are mineralogically related or commonly occur together in special geologic environments (figs. 22B–8–22B–12). Figure 22B–8 shows the distribution of carbonate minerals in the Kunduz AOI, whereas figure 22B–9 shows where clay minerals and micas occur. The distribution of iron-oxide and iron-hydroxide minerals is displayed in figure 22B–10. Minerals commonly found in hydrothermally altered rocks are mapped in figure 22B–11, and secondary minerals often associated with mineralized and (or) weathered rocks are mapped in figure 22B–12.

22B.4.1 Carbonate Minerals

Carbonate minerals, overwhelmingly calcite, were mapped over the majority of the Kunduz AOI where it is not covered with substantial vegetation (fig. 22B–8). In general, calcite is mapped within every geologic unit. Small concentrations of pixels that potentially contain dolomite are distributed in the center of the area covered by the imaging spectrometer data.
22B.4.2 Clays and Micas

A mixture of clays with carbonates was the primary material mapped in the AOI. Pixels containing these mixtures are detected in distinct patterns, especially in early Miocene geologic units. The pixels that match the chlorite or epidote class do not occur in a spatially consistent pattern and are likely the result of noise in the imaging spectrometer data rather than the presence of these minerals.

22B.4.3 Iron Oxides and Iron Hydroxides

The Kunduz AOI contains conspicuous areas of hematite in the center of area (fig. 22B–10). Large concentrations of hematite appear in early Miocene and Eocene units. In early Miocene units, the distribution of hematite mimics that of the clay (see fig. 22B–9) and probably corresponds to the red clays described in that unit. Associations of hematite with clays occur elsewhere in the area, most obviously in the hematites along the eastern edge of the Kunduz AOI (fig. 22B–10).
Figure 22B–7. Map of iron-bearing minerals and other materials derived from HyMap data in the Kunduz area of interest.

22B.4.4 Common Alteration Minerals

Most of the minerals in this group are commonly present in hydrothermally altered rocks associated with epithermal mineral deposits (fig. 22B–11). Consequently, where they occur in distinct clusters is of great interest in terms of potential mineral deposits. However, the mineral distributions do not occur in distributions that are suggestive of such alteration in the Kunduz AOI.

22B.4.5 Common Secondary Minerals

Secondary minerals, in the epidote and chlorite or epidote classes (fig. 22B–12), occur in scattered patterns in the Kunduz AOI, likely a result of noise in the imaging spectrometer data in areas of dry vegetation and (or) carbonates, which can lead to spurious false-positive detections of these minerals.
22B.4.6 Celestite

The Kunduz celestite deposit (Abdullah and others, 1977) was not covered by the airborne survey. Kokaly and Johnson (this volume) report on the preliminary analysis of imaging spectrometer data covering the Tangi-Murch celestite deposit in the Dudkash AOI.

22B.5 Summary

Green and dry vegetation cover most of the Kunduz AOI. In the areas with exposed rocks and soils, carbonate minerals are the most abundant. Associations of hematite with clays are consistent with red clays of the Early Miocene units in the area. The Kunduz celestite deposit (Abdullah and others, 1977) was not covered by the airborne survey.
Figure 22B–9. Map of distribution of clay and mica minerals derived from HyMap data in the Kunduz area of interest.
Figure 22B–10. Map of distribution of iron-oxide and iron-hydroxide derived from HyMap data in the Kunduz area of interest.
Figure 22B–11. Map of distribution of common alteration minerals derived from HyMap data in the Kunduz area of interest.
Figure 22B–12. Map of distribution of common secondary minerals derived from HyMap data in the Kunduz area of interest.

22B.6 References Cited


