Chapter 4B. Analysis of Imaging Spectrometer Data for the Balkhab Copper Area of Interest

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Abstract

Hyperspectral remote sensing data collected over the Balkhab area of interest (AOI) in northern Afghanistan were analyzed with spectroscopic methods to identify the occurrence of selected materials at the surface. The area is believed to have the potential for volcanogenic massive sulfide, coal, and possible gold deposits. Absorption features in the spectra of HyMap data were compared to a reference library of spectra for known materials. Carbonates and vegetation cover most of the Balkhab AOI. Distinct patterns of muscovite, kaolinite, chlorite or epidote, and montmorillonite occur in localized patterns, especially along the river that crosses through the center of the AOI. Analysis of the HyMap data also detected small but distinct occurrences of jarosite, hydrated silica, and pyrophyllite, all of which may be associated with hydrothermal alteration. The Balkhab Prospect is mapped within the vegetation class, but the surrounding Ordovician-age rocks are mapped as illite, muscovite, chlorite or epidote, calcite, and Fe$^{2+}$ Fe$^{3+}$ Type 2 and Fe$^{2+}$ Fe$^{3+}$ Type 1 mineral classes.

4B.1 Introduction

Past studies of geologic data of Afghanistan revealed numerous areas with indications of potential mineral resources of various types (Abdullah and others, 1977; Peters and others, 2007). Several of these areas were selected for additional studies using imaging spectroscopy to characterize surface materials. Imaging spectroscopy is an advanced type of remote sensing also known as hyperspectral remote sensing. One such area selected for imaging spectroscopy is the Balkhab area of interest (AOI) in northern Afghanistan, which is approximately 230 kilometers (km) northwest of Kabul (fig. 4B–1). The area is believed to have the potential for volcanogenic massive sulfide, coal, and possible gold deposits. 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. This report contains the results of the spectroscopic data analyses and identifies sites within the Balkhab AOI that deserve further investigation, especially detailed geologic mapping, lithologic sampling, and geochemical studies.

4B.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, oil, and gas) and earthquake hazards in the country (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 be used to characterize only the upper surface materials and not subsurface composition or structure. Subsurface processes can be indicated, however, by the distribution of surface materials.
4B.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 from 0.43 to 2.48 micrometers (µm) in 128 channels. The imaging spectrometer was flown on a WB-57 high-altitude aircraft at approximately 50,000 feet. 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 square kilometers (km²) (Kokaly and others, 2008). Data were received in scaled radiance (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 that overlapped between detectors were removed from the image cubes. Each flight line was georeferenced to Landsat base imagery in Universal Transverse Mercator (UTM) projection (Davis, 2007).

4B.2.2 Calibration

HyMap data were converted from radiance to reflectance using a multi-step process. This calibration 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 typical 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.). The ACORN program was run multiple times for each flight line using average elevations in 100-meter (m) increments, covering the range of minimum to maximum elevations encountered within the flight line. A single atmospherically corrected image was assembled from these elevation-incremented ACORN results 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. Spectra of five ground calibration sites were collected in Afghanistan: field spectra from Kandahar Air Field, Bagram Air Base, and Mazar-e-Sharif Airport, as well as laboratory spectra of soil samples from two fallow fields in Kabul. These were used to calculate empirical correction factors using the pixels of atmospherically corrected HyMap data in the flight lines that passed over the sites. The empirical correction from the closest calibration site to each flight line was then applied.

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 the result of a 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. Over the course of the data collection process, the sun angle, atmospheric water vapor, and atmospheric scattering differed for each flight line. To compensate for this variation, 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 each standard data line, typically oriented north-south, was derived using the pixels of overlap with the well-calibrated cross-cutting line that intersected it, 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 region of overlap, reduced residual atmospheric contamination in the imaging spectrometer data that may have been present after the ground calibration step.

4B.2.3 Materials Maps and Presentation

After the calibration process, the reflectance data were georeferenced and then analyzed using the Material Identification and Characterization Algorithm (MICA), a module of the USGS Processing Routines in Interactive Data Language (IDL) for Spectroscopic Measurements (PRISM) 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 best spectral match to each pixel was determined, and the results were clustered into classes of materials discussed next. The resulting maps of material distribution, resampled to a 23 × 23-m square pixel grid, were mosaicked to create thematic maps of surface mineral occurrences over the full data set covering Afghanistan.

The MICA module was applied to HyMap data twice in order to present the distribution of two categories of minerals naturally separated in the wavelength regions of their primary absorption features. MICA was applied using the subset of minerals with absorption features in (1) the visible and near-infrared wavelength region to produce the 1-µm map of iron-bearing minerals and other materials (King, Kokaly, and others, 2011), and (2) the shortwave infrared region to produce the 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 colors required to represent the mineral classes.

The iron-bearing minerals analysis includes 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 mineral compositions but comparable spectral features are less easily distinguished; therefore, some identified classes consist of several minerals with similar spectra, such as the “chlorite or epidote” class. When comparisons with reference spectra resulted in no viable match, a designation of “not classified” was assigned to a pixel.

### 4B.3 Geologic Setting of the Balkhab AOI

The Balkhab AOI is mainly within Sari Pul Province in northern Afghanistan, with small sections located in Balkh and Samangan Provinces. The Balkhab AOI is 1,858 km$^2$, of which the Balkhab Prospect subarea covers 321 km$^2$. The contrast-enhanced stretch of the natural-color composite of Landsat Thematic Mapper bands shown in figure 4B–2 provides a general overview of the Balkhab 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.

#### 4B.3.1 Topography

Land elevation within the Balkhab AOI ranges from 951 to 4,028 m (fig. 4B–3). The low areas within the Balkhab AOI follow a river that crosses the region lengthwise, flowing from the southwest toward the northeast. The highest areas surround the river basins throughout the AOI. The main population center is the district center of Balkhab in the western part of the AOI.

#### 4B.3.2 Lithology and Structure

Rocks in the Balkhab area range in age from Ordovician to Early Miocene (fig. 4B–4; Doebrich and Wahl, 2006; Abdullah and Chmyriov, 1977). The oldest rocks are Ordovician-age stratified formations composed of sandstone, siltstone, shale, limestone, and chert that are exposed along parts of the river basin. Also present along the river basin and the lower sections of secondary streams are Silurian-Devonian schists and sheared metamorphic rocks. The only other intrusive type rocks are of Mississippian age and consist of dunite, peridotite, and serpentine, all of which occur along the southern border of the AOI just south of the Balkhab Prospect subarea. Two of the younger, abundant rock units in the Balkhab AOI are Late Cretaceous undifferentiated rocks of sandstone, siltstone, clay, limestone, marl, conglomerate, gypsum, and redstone, and Maestrichtian-Paleocene rocks of limestone, marl, dolomite, sandstone, clay, siltstone, gypsum, and conglomerate. The main sedimentary units seem to occur at higher elevations.
4B.3.3 Known Mineralization

Figure 4B–5 shows one location where mineralization having a potential for mineral resource development may exist (Abdullah and others, 1977; Peters and others, 2007). There is only one volcanogenic massive sulfide prospect in the Balkhab AOI. The characteristics of the mineralized location are summarized in table 4B–1.

Table 4B–1. Sites of known mineralization in the Balkhab area of interest.
[Data are from Peters and others (2007). Cu, copper; VMS, volcanogenic massive sulfide]

<table>
<thead>
<tr>
<th>Name</th>
<th>Deposit type</th>
<th>Major commodity</th>
<th>Deposit size</th>
<th>Alteration</th>
<th>Mineralogy</th>
<th>Gangue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balkhab</td>
<td>VMS</td>
<td>Cu</td>
<td>Occurrence</td>
<td>Silicification; limonitization</td>
<td>Pyrite; malachite; galena</td>
<td>Quartz</td>
</tr>
</tbody>
</table>

Copper in the Balkhab Prospect is hosted in sulfide rich rocks where pyrite, galena, and malachite are present. The Balkhab Prospect plus various other copper showings occur in Paleozoic rocks (Abdullah and others, 1977; Doebrich and Wahl, 2006; Peters and others, 2007). The largest beds
are up to 5 km long with thicknesses from 300 to 400 m (Abdullah and others, 1977; Doebrich and Wahl, 2006). Smaller beds are believed to be 300 to 400 m long with thicknesses of 20 to 50 m.

Figure 4B–3. Map showing the range of elevations in the Balkhab area of interest.

4B.3.4 Data Limitations

Geographic registration between various datasets is not always possible because of differences in collection methods and resolution. The geographic accuracy and quality of each dataset is limited by the original source. Significant efforts were made to ensure the geographic accuracy of the HyMap data (Kokaly and others, 2008; Hoefen and others, 2010); however, exact registration between previously published known mineral occurrences, fault traces, geologic units, and structural boundaries in comparison to the HyMap data may not be ideal. To resolve additional details, the digital versions of these maps can be viewed at higher spatial resolutions than is possible for a single-page printed map.
Figure 4B–4. Geologic map of the Balkhab area of interest. Geology from digital geologic map of Afghanistan (Abdullah and Chmyriov, 1977; Doebrich and Wahl, 2006; Peters and others, 2007).
4B.4 **Mineral Maps of the Balkhab Area of Interest**

Analysis of the HyMap imaging spectrometer data of the Balkhab AOI using spectroscopic methods resulted in the identification of a wide variety of minerals exposed at the surface. Although the occurrence of certain minerals 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, knowledge about 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.

Figure 4B–6 depicts the results of the MICA analyses of the HyMap data for the Balkhab AOI for the 2-µm materials, which include carbonates, phyllosilicates, sulfates, altered minerals, and other materials. The carbonate mineral groups cover most of the Balkhab AOI, as indicated by pixels mapped as calcite and calcite mixed with clay/mica. Pixels matching pure muscovite or illite spectra occur over large contiguous areas in the central and western portions of the river valley. Distinct patterns of kaolinite occur in spatially localized patterns, especially in the center and northwestern areas of the AOI. Large areas of chlorite or epidote were concentrated in the central river basin west and southwest of the Balkhab Prospect. Montmorillonite is present throughout the AOI in localized concentrations, usually in the river valleys.
Figure 4B–7 shows the mapping results for the iron-bearing minerals. The iron-bearing materials map is dominated by goethite to the southwest and Fe$^{2+}$ Fe$^{3+}$ Type 2 and Fe$^{2+}$ Type 1 along the river valley. There are a few spatially distinct occurrences of hematite and epidote throughout the AOI.

Figure 4B–6. Map of carbonates, phyllosilicates, sulfates, altered minerals, and other materials derived from HyMap data in the Balkhab area of interest.

Because of the large number of classes represented and the subtleties of the distribution patterns represented in these image 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 specific geologic environments. Figure 4B–8 shows the distribution of carbonate minerals in the Balkhab AOI whereas figure 4B–9 shows where clay minerals and micas occur. The distribution of iron oxide and hydroxide minerals are displayed in figure 4B–10. Minerals commonly found in hydrothermally altered rocks are shown in figure 4B–11, and secondary minerals often associated with mineralized and (or) weathered rocks are shown in figure 4B–12.

4B.4.1 Carbonate Minerals

Carbonate minerals, either calcite or dolomite, were detected over a large majority of the Balkhab AOI (fig. 4B–8). In general, calcite and calcite + muscovite/illite group minerals are detected throughout the AOI and within almost every geologic unit. Calcite + montmorillonite occurs along the upper part of the river valley. Dolomite or dolomite mixed with calcite and (or) clay occurs in smaller
contiguous areas that are mostly in the south-central and southwestern areas of the AOI. The known mineralized area is not highlighted in the carbonate minerals map.

Figure 4B–7. Map of iron-bearing minerals and other materials derived from HyMap data in the Balkhab area of interest.

4B.4.2 Clays and Micas

Abundant detections of muscovite and illite were mapped in units of Ordovician-age rocks along the central valley of the Balkhab AOI (fig. 4B–9). In addition, illites and muscovites were also detected within nearby Rhaetian and Early-Middle Jurassic stratified rock formations. Chlorite or epidote was detected in Ordovician-age stratified formations and Late Triassic intrusive rocks. Kaolinites were distributed within the Ordovician, Rhaetian, Early-Middle Jurassic, and Late Cretaceous rock formations in the river valley. The kaolinite occurrences start to occur 3.7 km northwest of the Balkhab Prospect (along a fault) and continue to map in the central to northeastern part of the AOI. South and west of this fault line, chlorite or epidote, muscovite, and illite dominate, whereas north and east of this fault, kaolinites are the dominant mineral group; this is especially true for the Ordovician rocks. A small occurrence of pyrophyllite (lat 35°29'38"N., long 66°47'47"E.) was mapped approximately 9.7 km to the south and slightly to the east of the Balkhab Prospect.
Figure 4B–8. Map of distribution of carbonate minerals derived from HyMap data in the Balkhab area of interest.

4B.4.3 Iron Oxides and Hydroxides

The Balkhab AOI contains small conspicuous areas of hematite in the western, southwestern, east central, and eastern portions of the area (fig. 4B–10) in Ordovician and Late Cretaceous age units. The description of the Late Cretaceous units includes redstone (Abdullah and Chmyriov, 1977; Doebrich and Wahl, 2006), which supports the HyMap mineral detections. The hematite is usually located within or near areas of goethite or Fe-hydroxide. Pixels mapped as goethite and Fe-hydroxide are more widespread across the AOI compared to hematite, and primarily occur in the western and southern parts of the AOI. Two spatially distinct areas of goethite and Fe-hydroxide are present in the central western part of the AOI (lat 35°23'57"N., long 66°38'49"E., and lat 35°24'06"N., long. 66°31'08"E.). Jarosite is mapped approximately 1.9 km south of the Balkhab Prospect in both the 1-µm (fig. 4B–7) and 2-µm (fig. 4B–6) materials maps. Jarosite is also found in smaller concentrations throughout the western portion of the AOI. Spatially distinct groupings of epidote were mapped in the north-central and southwestern parts of the AOI along the border (fig. 4B–10).
Figure 4B–9. Map of distribution of clay and mica minerals derived from HyMap data in the Balkhab area of interest.

4B.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. 4B–11). Consequently, where they occur in distinct clusters is of great interest in terms of potential mineral deposits. A small occurrence of pyrophyllite is present approximately 9.7 km to the south and slightly east of the Balkhab Prospect. Jarosite and hydrated silica were detected along a unit approximately 1.9 km south of the Balkhab Prospect (near lat 35°33'32"N., long 66°45'24"E.). Because of the importance of pyrophyllite as an indicator of potential epithermal processes, these two occurrences should be examined in greater detail as part of subsequent geophysical and geologic field investigations.

Kaolinite was detected in the river valleys in the southwestern and northeastern portions of the AOI. The chlorite or epidote class maps throughout the central river valley in the AOI. Carbonate (iron-bearing) is associated with the chlorite or epidote mineral group in the central valley (near lat 35°34'32"N., long 66°44'13"E.). The iron-carbonate is shown in greater detail in King, Johnson, and others (2011).
4B.4.5 Common Secondary Minerals

Secondary minerals, in the epidote, chlorite, and chlorite or epidote classes (fig. 4B–12) are primarily detected along the central river valley. In addition, there are well-defined groups of epidote and chlorite or epidote in the northeastern part of the Balkhab AOI. In the southern and western parts of the AOI, serpentine maps within the Silurian-Devonian, Late Permian, and Ordovician-age stratified formations and the Mississippian intrusive rocks.

4B.4.6 Balkhab Prospect Subarea

Detailed maps of the Balkhab Prospect subarea are presented in figures 4B–13 through 4B–23. The Balkhab Prospect is described as a volcanogenic massive sulfide (Peters and others, 2007, Abdullah and Chmyriov, 1977; Doebrich and Wahl, 2006). Figures 4B–13 through 4B–16 show, respectively, the contrast-enhanced natural color Landsat imagery, elevation data, geology, and a known mineral occurrence.
Figure 4B–11. Map of distribution of common alteration minerals derived from HyMap data in the Balkhab area of interest.

Figure 4B–17 depicts the results of the MICA analyses of the HyMap data for the Balkhab Prospect subarea for the 2-µm materials, which include clays, carbonates, sulfates, altered minerals, and other materials. The carbonate mineral groups cover a large percentage of the Balkhab Prospect area. Pixels mapped as muscovite or illite are present over large contiguous areas in the central and southwestern areas along the river valley. Kaolinite is detected as small distinct clusters, especially in the south-central and northwestern parts of the subarea. Large areas of chlorite or epidote group minerals were found concentrated in the central river basin west and southwest of the Balkhab Prospect (lat 35°34'46"N., long 66°44'01"E., and lat 35°32'13"N., long 66°41'03"E.). Montmorillonite is detected in localized groups commonly in the river valleys within the central part of the AOI. The close proximity of jarosite and hydrated silica minerals (lat 35°33'32"N., long 66°45'24"E.) and their importance as indicators of potential hydrothermal activity suggests the need for additional geophysical and geochemical investigation in the AOI.
If the known mineral occurrence location is accurate, then the Balkhab Prospect maps within the vegetation class, but appears to be located within Ordovician-age rocks. The Ordovician rocks in this area generally match the reference spectra of illite, muscovite, chlorite or epidote, and calcite. Minerals reported to be associated with the Balkhab Prospect include pyrite, malachite and galena (Peters and others, 2007; Abdullah and others, 1977). Pyrite and galena lack unique spectral features in the wavelength region of the HyMap data, thereby making detections of these minerals difficult. Malachite is not a commonly occurring mineral, and therefore, was not included in the spectral library. Future work could benefit from the addition of malachite to the spectral library, as this mineral could potentially be detected and mapped if it occurs in significant quantities that are exposed at the surface.
Figure 4B–13. Contrast-enhanced Landsat Thematic Mapper natural color image of the Balkhab Prospect subarea. Geologic units and faults are from Abdullah and Chmyriov (1977) and Doebrich and Wahl (2006).

Figure 4B–18 shows the results for the iron-bearing minerals. The majority of the iron-bearing minerals detected in the Balkhab Prospect subarea are mapped as Fe$^{2+}$ Fe$^{3+}$ Type 2 and Fe$^{2+}$ Type 1. Goethite maps in the valleys throughout the subarea, but at much lower levels than the surrounding areas. Again, the Balkhab Prospect is mapped within the vegetation class, but the surrounding Ordovician-age rocks are mapped as the Fe$^{2+}$ Fe$^{3+}$ Type 2 and Fe$^{2+}$ Fe$^{3+}$ Type 1 mineral classes.
Figure 4B–14. Elevations and topography of the Balkhab area of interest.

As noted earlier, the large number of classes represented and the subtleties of the distribution patterns represented make it useful to display the subarea results as a series of image maps, each depicting a selected group of minerals that are minerallogically related or commonly occur together in special geologic environments (figs. 4B–19 through 4B–23). Figure 4B–19 shows the distribution of carbonate minerals in the Balkhab Prospect subarea, mainly distributed at higher elevations. Dolomite and dolomite + montmorillonite/calcite group minerals were detected in small clusters in the southwestern portion of the subarea. Figure 4B–20 shows where clay minerals and micas occur. Chlorite or epidote and illite dominate the image along the river valley. A distinct boundary between the muscovites and illites and the kaolinite class minerals is observed in this region. The kaolinite group minerals start to occur 3.7 km northwest of the Balkhab Prospect along a fault and continue eastward into the central to northeastern area of the AOI. South and west of this fault line, chlorite or epidote, muscovite, and illite dominate, whereas north and east of this fault, the kaolinites are the dominant mineral group. The distributions of iron oxide and hydroxide minerals are displayed in figure 4B–21. This region lacks many iron oxide and hydroxide minerals, although small patches of goethite are
detected throughout the subarea. Minerals commonly found in hydrothermally altered rocks are mapped in figure 4B–22, and again, the chlorite or epidote and kaolinite group minerals are the major classes. A small occurrence of jarosite and hydrated silica is detected in the central portion of the subarea. Secondary minerals often associated with mineralized and (or) weathered rocks are mapped in figure 4B–23. The chlorite or epidote class is predominant, and serpentine minerals are mostly present in the southwestern part of the subarea.

Figure 4B–15. Geologic map of the Balkhab Prospect subarea (from Abdullah and Chmyriov, 1977; Doebrich and Wahl, 2006; Peters and others, 2007).
Figure 4B–16. Sites of known mineralization by deposit type (Peters and others, 2007) on the geologic map of the Balkhab Prospect subarea (from Abdullah and Chmyriv, 1977; Doebrich and Wahl, 2006; Peters and others, 2007).

4B.5 Summary

Carbonate minerals are detected throughout most of the Balkhab area of interest (AOI). Muscovites and illites were detected in greatest concentration in the mapped units of Ordovician and Silurian-Devonian age rocks in the central to southwest-central region of the Balkhab AOI, and in the adjacent units, suggesting that mineral distributions detected with HyMap data could be used to refine the locations of lithologic contacts. Epidote and chlorite were found in spatially consistent patterns concentrated along the central river basin west and southwest of the Balkhab Copper Prospect. Kaolinites were distributed within the Ordovician, Rhaetian, Early-Middle Jurassic, and Late Cretaceous rock formations in the river valley. The largest occurrences of kaolinite in the AOI are located in the central and northeastern river valleys. Two areas that may be associated with hydrothermal alteration are an area of pyrophyllite in the southern part of the AOI (lat 35°29'38"N., long 66°47'47"E.) and an area of jarosite and hydrated silica in the central part (lat 35°33'32"N., long 66°45'24"E.). These two areas should be studied in more detail with additional geophysical and geochemical characterization. Goethite and Fe$^{2+}$ Fe$^{3+}$ Type 2 dominate the iron-bearing materials map. Several areas of hematite are detected within areas of redstone, and are consistent with the geologic map.
Figure 4B–17. Map of carbonates, phyllosilicates, sulfates, altered minerals, and other materials derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–18. Map of iron-bearing minerals and other materials derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–19. Map of distribution of carbonate minerals derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–20. Map of distribution of clay and mica minerals derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–21. Map of distribution of iron oxide and hydroxide derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–22. Map of distribution of common alteration minerals derived from HyMap data in the Balkhab Prospect subarea.
Figure 4B–23. Map of distribution of common secondary minerals derived from HyMap data in the Balkhab Prospect subarea.

4B.6 References Cited


