

Characterizing Mineral Alteration Using Airborne Visible-Infrared Imaging Spectrometer Data at Questa, New Mexico

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Introduction

A baseline and pre-mining ground-water quality study of the Red River Basin in New Mexico is being undertaken by the U.S. Geological Survey. As part of this study, Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data were analyzed to characterize mined and non-mined ground along the Red River between the towns of Questa and Red River, New Mexico. This area has zones of intensely mineralized and altered ground that effect the water quality of Red River. Analysis of the reflectance data has identified mineral assemblages that can affect water quality by lowering the pH and introducing metals, salts, and sediments.

Data

The AVIRIS data (Green et al., 1998) were acquired by a single west to east NASA/JPL overflight on June 30, 1999. The flightline trends parallel to the Red River (that flows westward into the Rio Grande), starting at the town of Questa and ending east of the town of Red River imaging both sides of the river. The line starts at the west-bounding fault of the Taos Range with the Rio Grande Valley, and continues eastward following the deeply incised Red River valley.

Methods

NASA/JPL AVIRIS data were calibrated to ground reflectance, and analyzed using custom U.S. Geological Survey software and spectral mineral library (Clark et al., 1993a, 1993b, 1993c). Field examination was used to verify these results. This analytical approach has been developed and used over the past 13 years to map a range of geologic terrain, including porphyry systems and other hydrothermally altered ground. Identifiable minerals include a variety of iron hydroxides, sulfates, clays, micas, and carbonates.

A two stage process was used to calibrate the airborne radiance data to surface reflectance. An atmospheric model was first applied to remove atmospheric gas effects and convert the radiance data to estimated ground reflectance. The data was converted using the Atmosphere REMoval (ATREM) Program (Gao et al., 1997). Second, this estimated reflectance data was then calibrated to apparent ground reflectance using field spectra from a ground calibration site, to remove residuals from the ATREM processed data. Soil from this site was measured using an Analytical Spectral Devices (ASD) FR field spectrometer, then a multiplier and offset were derived using the ASD field spectra, the AVIRIS calibration site spectra, and AVIRIS spectra collected nearby in shadowed-heavily vegetated terrain (Clark et al., 2002a, this vol.).

During analysis of AVIRIS data, the U.S. Geological Survey's Tetracorder version 3.7a program (Clark et al., 2002b) was used to spectrally test the data against the U.S. Geological Survey's spectral library. Pixel spectra from AVIRIS were tested against several hundred mineral and mineral mixture library spectra using a goodness-of-fit algorithm. The fit value for the continuum removed absorption features between the pixel spectrum and each mineral library spectrum was used to indicate the likelihood of mineral identification. Further tests by the Tetracorder program used absorption band depth, continuum slope, and mineral exclusion rules to guide mineral identification. Mineral identification was completed through interactive analysis of the spectral data and output images and verified using selected sites in the field.

Spectral analysis identified and mapped a variety of minerals that were then associated with mineral assemblages. As an example, spectral features of one mineral assemblage (quartz-sericite-pyrite) are seen in the middle spectrum in figure 1, with the absorption features of sericite seen at 2.2 microns and jarosite (after pyrite) seen at 0.42, 0.50, 0.92, and 2.27 microns. Occurrence of sericite and jarosite are diagnostic in associating areas with the quartz-sericite-pyrite assemblage. The other spectra in figure 1 show representative absorption features for supergene kaolinite (2.17 & 2.22 microns) and goethite (0.50 and 0.92 microns). These two minerals are common throughout the district.

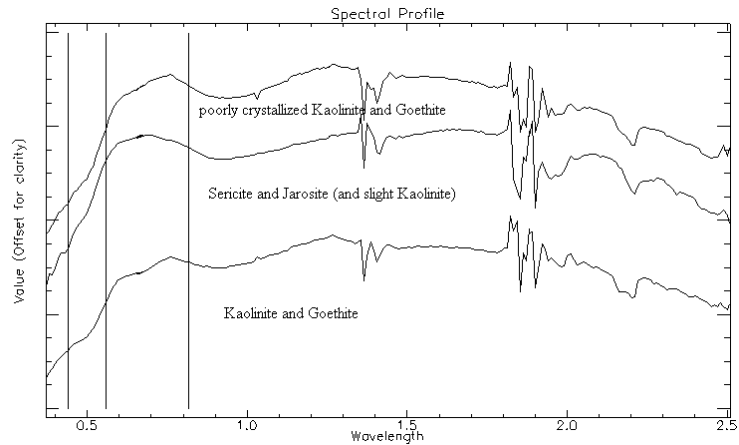


Figure 1. Single pixel spectra extracted from the Questa AVIRIS data showing absorption features of: Kaolinite (2.17 & 2.20), Sericite (2.2 & 3.5), Goethite (0.50 & 0.92), and Jarosite (0.42, 0.92, & 2.27 microns)

Constraints on mineral mapping at Questa were the lack of spectral character and low abundance of several important alteration, ore forming, and rock forming minerals, such as quartz, feldspar, pyrite, topaz, and biotite. Most quartz and feldspar do not have spectral responses in the AVIRIS wavelengths suitable for identification, while topaz and biotite are in low abundance. Abundant vegetation, especially on north slopes, covered rock and soil in many areas, preventing mineral identification.

Geologic History

The Red River flows westward from the Taos Range into the Rio Grande River, cutting through Precambrian rocks overlain in part by Tertiary volcanic rocks of the Latir volcanic field, along the southern edge of the 26-MA Questa caldera (Bethke and Lipman, 1989). The cogenetic volcanic and plutonic rocks host the alteration mineral assemblages and molybdenum mineralization in zones that trend east-west along the southern boundary of the caldera. The silicic alkalic rhyolite tuff ash-flow sheet that initially ponded within the caldera was subsequently fault tilted and brecciated, then intruded by batholithic granite rocks which set up the hydrothermal systems that altered and mineralized the country rock. Later faulting and deformation related to the Rio Grande Rift mechanically and chemically prepared the contact between the Tertiary granite stocks and the overlying tuff, allowing mineralizing fluids to form sheet vein and disseminated molybdenum ore bodies (Meyer and Foland, 1991).

Altered Mineral Assemblages

Igneous activity at Questa created hydrothermal (hot water) systems that episodically altered minerals within the country rock resulting in the formation of new minerals stable under the thermal, chemical, and pressure conditions of the hydrothermal cells. These altered minerals formed discrete assemblages that reflect or represent changes in chemistry and temperature of the hydrothermal system. The driving force for the system was the thermal energy derived from the cooling granite stocks, releasing hot magmatic solutions and heating ground waters. These hydrothermal fluids were driven upward, away from the granites, exchanging ions with the surrounding wallrock. A particular mineral assemblage is a function of its place in the hydrothermal system and the chemistry of the fluids at that point. Alteration assemblages recognized in the Questa AVIRIS data are:

Propylitic assemblage: an acid buffering assemblage of minerals including calcite, chlorite, and epidote, that are spectrally identified in the AVIRIS data. In particular, calcite is useful in buffering acid-water to more neutral pHs and precipitating metals held in solution. Propylitic alteration generally forms as a

regional early stage alteration, distal to the mineralizing center and can be locally replaced by later more intense alterations. The assemblage can also form also as a retrograde late stage product in the hydrothermal system.

Quartz-sericite-pyrite (QSP) assemblage: a suite of minerals whose sulfide content is potentially acid-generating. Sericite can be spectrally identified directly, while pyrite is inferred through the spectral identification of jarosite, an iron sulfate formed through the weathering of pyrite and other sulfide minerals. QSP alteration commonly is a moderately intense alteration assemblage that can be wide spread, altering the country rock into material that may have high acid-water generation potential and high leachable metal content, that formed later in the alteration process. Sericite, as used in this manuscript, refers to various grain-sizes of muscovite, and the clay illite, which have similar spectroscopic features.

Advanced argillic assemblage: an assemblage that indicates higher formation temperatures with associated sulfur, such as found in local hydrothermal feeder systems and pipes. Kaolinite, pyrophyllite, and alunite, common minerals associated with advanced argillic alteration, have been spectrally identified in peripheral zones at Questa. These minerals are also created through supergene weathering at Questa.

In addition to altered mineral assemblages, later supergene weathering has formed altered minerals that have potential for effecting the environment. In the moist, oxygenated near neutral pH surface environment, iron-rich minerals have been converted to goethite; in a lower pH setting, pyrite and other sulfides have been converted to jarosite, gypsum, and alunite while feldspar is altered to kaolinite. Occurrence of jarosite, gypsum, alunite, and kaolinite suggest acidic conditions with sulfur content in the country rock (Meyer and Leonardson, 1990; Titley, 1994). Further weathering and neutralization will convert jarosite into goethite.

Mineral Maps

The iron-bearing mineral map (fig. 2) shows the supergene weathering minerals jarosite (after pyrite) and goethite (after iron-rich minerals). Jarosite indicates areas of potential acid-water generation

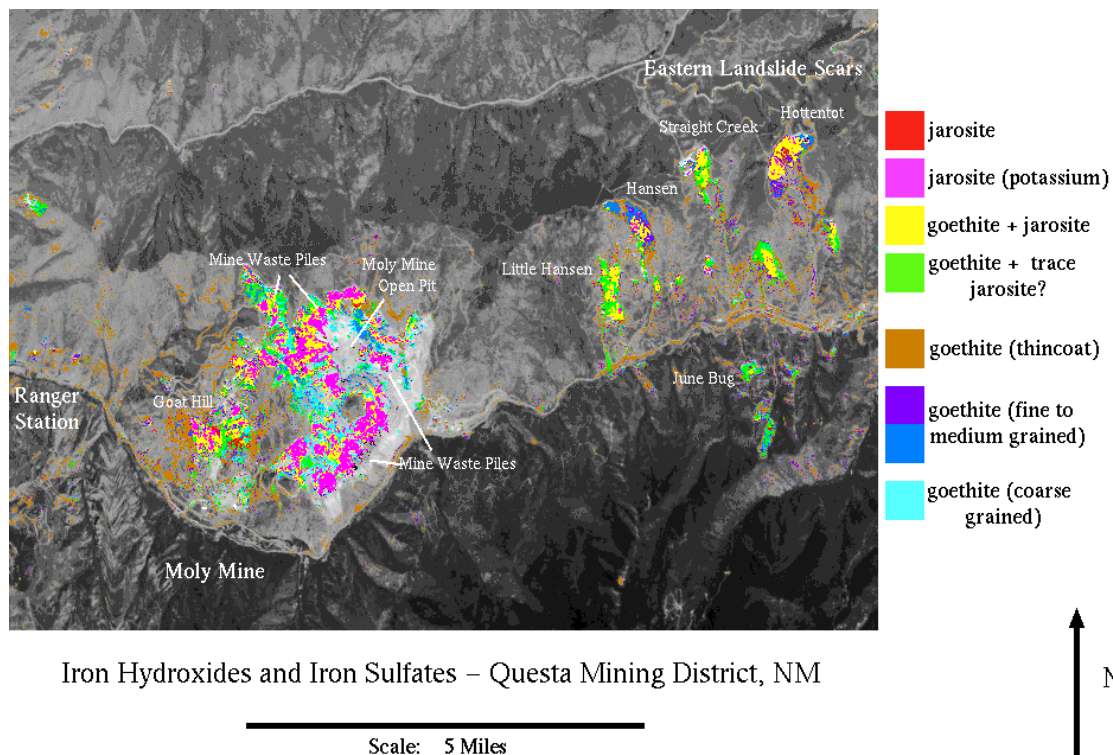


Figure 2. Iron bearing altered minerals; with the Landslide 'Scar' areas on the east and the Moly Mine complex on the west-center.

created by the breakdown of pyrite and other sulfides that form sulfuric acid. Jarosite is not stable under surface conditions and will break down into iron-oxides as its environment becomes neutralized (Bigham et al., 1992). Goethite indicates less acidic regions, where ferric iron is released by mafic minerals, or where neutralization of sulfide rich ground converts jarosite to goethite (Swayze et al., 2000). Note, the map indicates, and field examination confirms, little if any, hematite in contrast to acid-sulfate systems like Cuprite, Nevada.

The clays, micas, and sulfates mineral map (fig. 3) show the main alteration minerals due to ore forming processes. Most importantly, the quartz-sericite-pyrite assemblage is expressed by the wide occurrence of sericite at the Moly Mine site and also at the eastern landslide 'scar' areas. Kaolinite, some of which could be primary, is most commonly a secondary mineral due to supergene weathering and is associated with sericite. Other supergene minerals are gypsum and jarosite. The presence of these minerals suggest strong acid-water generation potential.

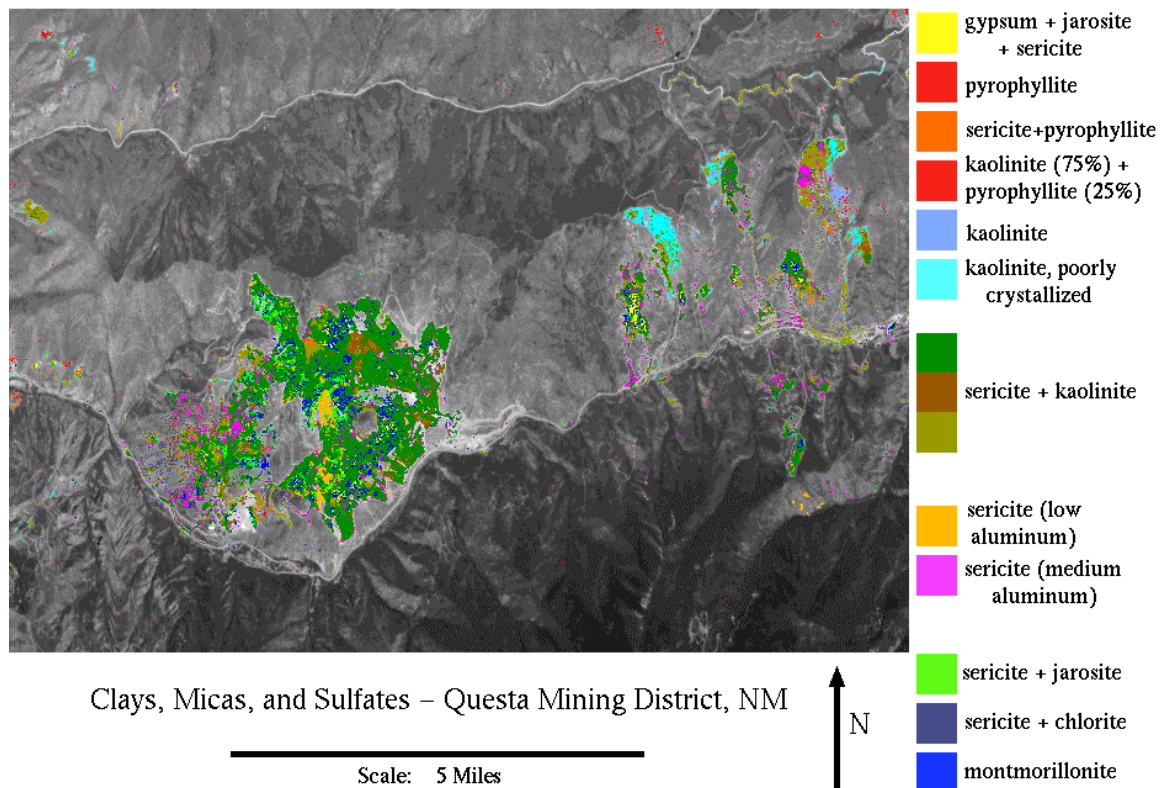


Figure 3. Clay, Mica, and Sulfate altered minerals.

The carbonates, alunite, and epidote mineral map (fig. 4) show regions potentially buffered by the propylitic assemblage minerals calcite and epidote, and includes chlorite (fig. 3). Calcite an important neutralizer of acid-water, occurs down gradient from the altered areas, and may serve to naturally buffer the groundwater. The extensive propylitic zone forms distal halos surrounding the more intensely altered centers seen in figure 2 and 3.

(For digital copies of these mineral maps, see: Livo and Clark, 2002)

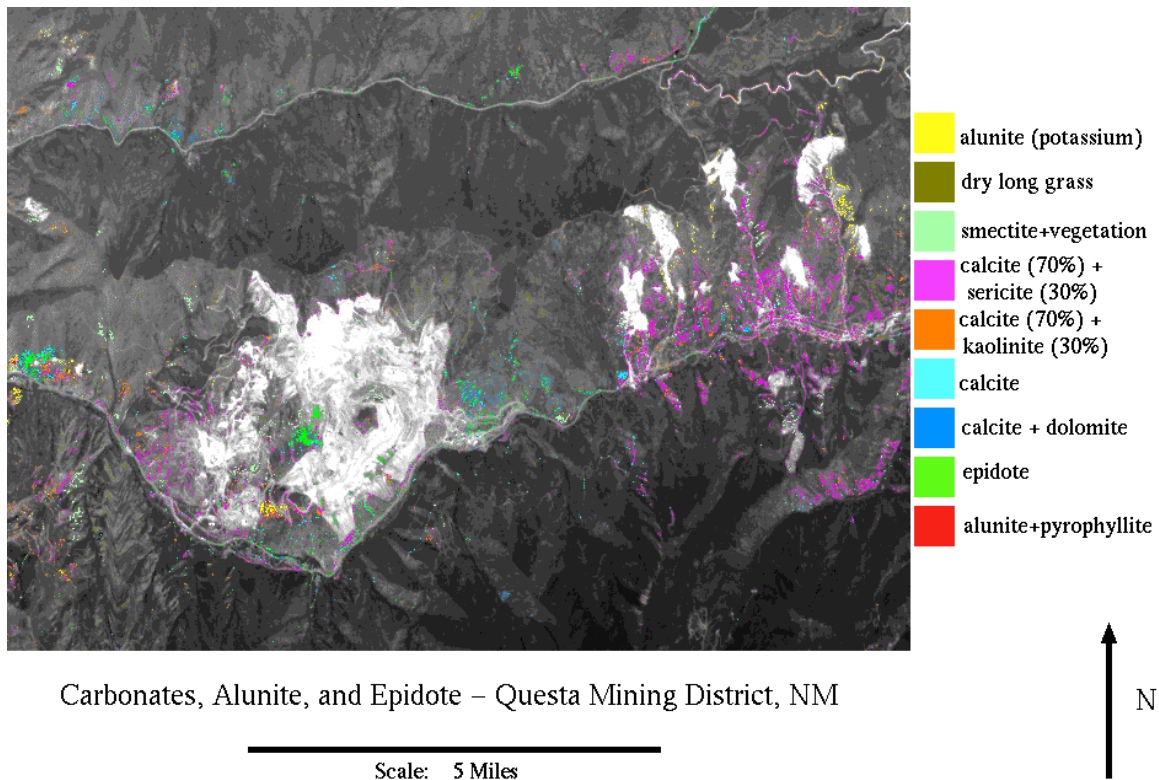


Figure 4. Carbonate, Alunite, Epidote, and Pyrophyllite altered minerals.



Figure 5. Eastern landslide 'Scar' areas with debris flow. Looking northeast at Lt. Hansen and Hansen landslide 'Scar' surfaces.



Figure 6. Goat Hill Gulch, looking north.

Results

Mineral maps of the eastern landslide ‘scar’ areas (Little Hansen, Hansen, Straight Creek, Hottentot, and June Bug – east side of the figs. 2, 3, and 4 image; and fig. 5) show key altered minerals that comprise the propylitic and quartz-sericite-pyrite assemblages, and the minerals due to supergene weathering. Sericite, goethite, jarosite, kaolinite, pyrophyllite, and gypsum are found in the scar areas, suggesting strong sulfide mineralization that is also expressed by the denuded terrain. Supergene jarosite, gypsum, and kaolinite signify on-going erosion and weathering of fresh steep surfaces that form the commonly seen debris flows along the steep gully floors. The weathering of altered minerals within the landslide areas breaks up the rock, weakens the slopes, and exposes metals confined within the rock to dissolution (Crowley and Zimbelman, 1997). The erosion rate in the landslide areas is moderate to high, especially during storm events, so metal leach and solid transport rates are potentially moderate to high. These conditions suggest that the potential for acid-water conditions exist with the possibility of metal leaching in these drainages. Notably, the altered mineral package of sericite with kaolinite, jarosite with goethite, and gypsum indicate that the supergene weathering in the scar areas is in a semi-steady-state condition. Propylitically altered rock surrounds the scars, notably on the downhill side, which could mediate any acid-drainage. During storm events, however, altered mineral debris flows will overwhelm any steady-state buffering the down-gradient propylitic minerals may supply, as demonstrated by the alluvial fans at the base of each landslide drainage.

Between the Moly Mine and eastern scar areas lies a block of propylitically altered ground. Calcite (fig. 4) is identified throughout the region (where the ground surface is exposed), suggesting a break in near surface mineralization between the Moly mine and eastern scar areas.

The Moly Mine site (the large altered area in the west-central part of the image) encompasses the Goat Hill Gulch scar area (western part of area), the Sulfur Gulch (north) scar area and associated open-pit mine (northeast), and the surrounding mine waste-rock piles (north, east, and south part of the Moly Mine area). These regions are all highly altered, mainly with a quartz-sericite-pyrite assemblage, although, advanced argillic (or supergene) pods do occur peripheral to the core zone. Abundant epidote occurs at the top of the ridge that separates Goat Hill Gulch from Sulfur Gulch, suggesting that the ridge forms the top of the hydrothermal system that is exposed to the west and east, in topographically lower ground. The degree of alteration identified in the AVIRIS data is similar at the non-mined Goat Hill Gulch area (fig. 6) and Sulfur Gulch, with its mined ground and non-mined scar areas. Of note is the relation of jarosite, which indicates acid-water and metal leaching potential, with elevation at Sulfur Gulch. It appears that jarosite abundance decreases with depth from the top of the alteration system (from the pre-erosion and pre-mining surface), suggesting a strong decrease in sulfide content of the wallrock. This relation is also expressed in the waste-rock piles, with rock extracted from the top of the alteration system (and dumped topographically high) containing higher abundance of jarosite. The erosion rate of the Moly Mine scar areas appears to be similar to the eastern scar region, though open-pit mining has highly accelerated the exposure of fresh material to weathering and possible leaching of metals (Shaw, Wels, and Robertson, 2002), as seen by the high abundances of jarosite in the mine-waste rock. The overall intensity of the quartz-sericite-pyrite alteration appears to be stronger at the Moly Mine area than in the eastern scar areas. Jarosite is more abundant at the non-mined Goat Hill Gulch and the non-mined top of Sulfur Gulch, in comparison with the non-mined eastern scar areas. Similar to the eastern scar areas, calcite and chlorite occur on the downhill sides of the alteration cores, possibly buffering to an extent, any acid-drainage. The lesser amount of goethite, the abundance of jarosite, and the lower abundance of kaolinite and gypsum indicate the higher degree of mineral alteration and the lack of steady-state weathering of the Moly Mine area (mined and non-mined), compared to the landslide areas. While no mine waste pile material is seen entering the Red River in figures 2, 3, and 4, historic altered material from debris fans at Goat Hill and Sulfur Gulches do and the southwestern part of the Goat Hill altered area extends to Red River.

The northeastern extent of the Log Cabin (far southwest part of image) area of alteration shows small, dispersed occurrences of kaolinite and goethite within a highly vegetated region, indicating the occurrence of mineralization that was known to exist on the basis of previous field mapping. At the northern edge of the area (most westward part of image bisected by Red River) a small advanced argillic (or supergene weathered) center containing pyrophyllite, sericite, gypsum, and alunite, is surrounded by

propylitically altered rock containing calcite and epidote. This area suggests a potential for acid-water generation with some buffer capability.

Conclusions

Hydrothermally altered and weathered minerals were mapped at Questa, New Mexico using the AVIRIS JPL/NASA imaging spectrometer. These minerals were grouped in propylitic and quartz-sericite-pyrite mineral assemblages and as supergene minerals that were used to infer surface environmental conditions and effects on the water quality of Red River.

Altered materials from the eastern landslide areas (Hottentot, Straight Creek, June Bug, Hansen, and Little Hansen Gulches and the Moly Mine area), mined ground and Sulfur and Goat Hill gulches have the potential to adversely effect the water quality of Red River. Debris trails and fans are associated with all the gulches that have mineralized rock that produce sedimentation in Red River, which possibly could introduce metals either through mass transport or through leaching into the river. These materials have low pHs and could generate acid-water that could strongly alter water quality, especially during spring runoff or during a storm event. Both mined and non-mined Moly Mine areas appear to have slightly more intense mineral alteration and less of a steady-state supergene weathering environment compared to the eastern landslide areas, though both mineralized regions are intensely altered. The Moly Mine area is well exposed through mining in the AVIRIS data, but the landslide areas appear to have similar environmental degrading potential as expressed by similar mineral alterations and the large area of altered ground seen through the vegetation.

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